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Well-to-wheel assessment of natural gas vehicles and their fuel supply infrastructures – Perspectives on gas in transport in Denmark

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ABSTRACT

In this paper, potential natural gas and renewable natural gas supply pathways and natural gas vehicles (NGVs) have been selected and evaluated with regards to well-to-wheel energy expended, greenhouse gas (GHG) emissions, and regulated (air pollutant) emissions. The vehicles included in the evaluation are passenger cars, light-duty vehicles (LDVs), and heavy-duty vehicles (HDVs) for road-transport applications, and a short-range passenger vessel for maritime transport applications. The results show that, compared to conventional fuels, in both transport applications and for all vehicle classes, the use of compressed and liquefied natural gas has a 15–27% GHG emissions reduction effect per km travel. The effect becomes large, 81–211%, when compressed and liquefied renewable natural gas are used instead. The results are sensitive to the type and source of feedstock used, the type of vehicle engine, assumed methane leakage and methane slip, and the allocated energy and environmental digestate credits, in each pathway. In maritime applications, the use of liquefied natural gas and renewable natural gas instead of low sulfur marine fuels results in a 60–100% SOx and 90–96% PM emissions reduction. A 1% methane slip from a dedicated LNG passenger vessel results, on average, in 8.5% increase in net GHG emissions.

1. Introduction

The EU-27 countries reduced their total greenhouse gas (GHG) emissions during 1990–2014 by 23%. However, due to increased transport demand and low share of renewables, in the same period, the transport sector's GHG emissions increased by 20.1% (European Enviromental Agency, 2017). Road transport accounted for 73% of the total emissions in 2014.

Recently, in addition to improving vehicle efficiency, the development and use of alternative fuel vehicles has become increasingly important to decarbonise the transport sector. With a high energy-to-carbon ratio, stable and low price, and abundant availability natural gas (NG) is an alternative to conventional transport fuels. Its low energy density (resulting in limited driving ranges) and low cetane number (restricting its use in compression engines without pilot diesel injection) are technical limitations. However, generally, natural gas vehicles (NGVs) could increase the fuel diversity by adding renewable natural gas (RNG) and NG into the petroleum-dominated transport sector while alleviating the driving range shortcomings of battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (HFCVs). This approach could potentially reduce air pollutant emissions in metropolitan areas.

Globally, as of 2016, there are more than 23 million NGVs are on the road, comprising 1.32% of the total vehicle population

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(IANGV, 2016); 66% in Asia Pacific, 24% in Latin America, 8.6% in Europe, and 1.4% in Africa and North America. Compared to the market development in Asia Pacific and Latin American countries, in Europe the development is slow, except for a few countries such as Italy, Germany, and Sweden (Engerer and Horn, 2010; IANGV, 2016).

The environmental advantages of NGVs are mostly reported in terms of on-board combustion alone or tank-to-wheel (TTW) analysis. In this regard, knowledge of the well-to-wheel (WTW) overall emissions, energy demand, and fuel production cost of alternative technologies is critical for its adoption and metering its true economic values over conventional transport technologies.

Diesel is the primary fuel in heavy duty vehicles (HDVs). In road-transport, HDVs are a main source of air pollutants, mainly NOx and PM (Durbin et al., 2008; Huai et al., 2006). In Europe, HD trucks account for around 10% of the vehicle population in urban areas, but their emission and noise levels account for more than 40% (Zunder and Ibanez, 2004). As a clean burning fuel, NG most importantly could replace diesel in HDVs for air pollutants abatements better than other fossil fuel-based alternative fuels (Osorio-Tejada et al., 2017). Alamia et al. (2016) showed the WTW GHG emissions reduction of biomethane (based on thermal gasification of woody biomass) and compressed/liquefied natural gas (CNG/LNG) over diesel, in HDVs, to be as high as 67% and 15%, respectively; however, the WTW energy consumption of biomethane was almost twice that of diesel in most cases. CNG buses were found to have lower marginal cost of GHG emissions reduction than diesel buses (McKenzie and Durango-Cohen, 2012). In DENA (2014), it was shown that the source and transport distance of LNG to retail points and the thermal efficiency of the engine largely determines the environmental advantages of LNG in HD trucks. In the European C-segment (medium) car applications, CNG showed a lower WTW GHG emissions but a higher WTW energy consumption than petrol/diesel cars (JRC, 2014). In Arteconi et al. (2010), based on the European gas mix, the use of an LNG import terminal showed a 10% WTW environmental advantage over diesel while an on-site small scale LNG plant showed zero advantage. On the other hand, Curran et al. (2014) suggested using NG in gas turbines for powering EVs instead of direct on-board combustion in NGVs.

Recently, real-world emission characteristics of NGVs were investigated, i.e. bi-fuel (CNG and gasoline) cars (Yao et al., 2014), light-duty vehicles (LDVs) (Huo et al., 2012; Karavalakis et al., 2012; Zhang et al., 2010), and HDVs (Lou et al., 2013; Zhang et al., 2014), questioning the energy and environmental advantages of using NG as vehicle fuel. CNG refuse trucks showed a substantial cut in NOx and PM emissions, but limited effect for CO and HC emissions, compared to diesel refuse trucks (Fontaras et al., 2012). In Karavalakis et al. (2012), it was shown that the NG composition has a direct impact on the fuel economy and CO_2 and non-methane hydro carbon (NMHC) emissions of LDVs.

For maritime transport applications, LNG is becoming widely accepted as a potential alternative fuel, driven by the newly imposed 0.1% sulfur limit on vessels cruising within emission control areas (ECA)[1] and the increasingly stringent environmental regulations for open seagoing vessels at large (International Maritime Organization (IMO), 2016). As of 2015, globally, about 70 LNG ships (excluding LNG carriers) were in operation, predominantly regional ferries (38%) and platform supply vessels (27%), and 80 ships were under construction (expected to be ready by 2018). Norway is in the vanguard with more than 59% of the worldwide operational LNG ships. The main market drivers in Norway are the nationally allocated NOx fund[2] and taxes imposed on NO_x, CO_2 and SO_x (Høibye, 2014). Globally, some of the challenges often referred to are lack of bunkering standards and regulatory framework, reduced cargo space (due to LNG fuel tank), bunkering losses, availability of bunkering ports, and high upfront vessel added cost (Eise Fokkema et al., 2017).

Methane leakage during bunkering might potentially offset the overall environmental advantages of LNG; in Corbett et al. (2015) it was reported that a 1% methane leakage increases the net GHG emissions of the vessel by 8.2–10% and in Chryssakis et al. (2015) that, on a WTW basis, a 5.5% methane leakage would result in zero GHG emissions reduction advantage over diesel fuel.

Jafarzadeh et al. (2017) showed that the price gap (between LNG and MGO) and tax level on NO_X and SOx are important factors in the conversion of marine gas oil (MGO) fishing vessels into LNG vessels and for the improvement of the environmental profile of the fishing industry at large. In addition, the level of presence in ECA areas, price gap (MGO/LNG), and vessels' fuel consumption are critical for the profitability of LNG vessels over conventional vessels (Eise Fokkema et al., 2017).

Due to computational and modelling framework limitations, techno-economic modelling of alternative technologies lacks the ability to capture the energy consumption and GHG and air pollutant emissions associated with the production of alternative fuels. Several of the studies related to the evaluation of energy and environmental performance of alternative technologies in transportation and stationery service demands demonstrated that TTW analysis alone would not be enough to characterise and understand the true environmental and energy values of alternative technologies. This strongly suggests that a detailed WTW analysis is essential in fully understanding the energy and environmental impact of alternative technologies, and for consistent comparison between alternative technologies. In addition, most prior WTW studies focused on macro-level analysis, and a detailed and site-specific analysis would be of interest in the light of the importance of the local energy infrastructure and context, as it is plausible that it could capture details that would otherwise be usually ignored. Thus, the aim of this study is to analyse the WTW energy consumption, GHG emissions, and air pollutant emissions of selected compressed/liquefied renewable natural gas (CRNG/LRNG) and CNG/LNG fuel supply pathways[3]

[1] Emission control areas (ECAs) are: the Baltic Sea (only for SOx), the Northern Sea (only for SOx), the North America area (SOx, NOx, and PM), and the United States-Caribbean Sea (SOx, NOx, and PM).

[2] The Norwegian government imposed a tax on NOx emission (about 2 €/kg NOx from ships, fishing vessels, and other industries) and allocated the NOx fund for reducing measures. LNG-fuelled ships are eligible for 25 €/kg annual NOx emission reduction support, with a maximum amount equivalent to 75% of the additional investment costs of LNG propulsion.

[3] Pathway refers to a specific predetermined route designed to supply fuel to vehicles. Throughout the paper, we used the prefix 'selected' because we selected few pathways out of many gas supply possibilities; based on resource availability, infrastructure development or readiness, and other factors that related to Denmark.

and gas vehicles within a national energy system context.

In light of this objective, the specific research questions addressed in this study are:

(1). What is the emissions profile of gas in transportation? Is it impact reducing,[4] impact avoiding or impact inducing over conventional fuels?
(2). Which gas vehicle technologies are more relevant in terms of GHG and air pollutant emissions reduction, if any?

The study will focus on conditions representing Denmark. There are several reasons for selecting Denmark as a case: considerable domestic natural gas production, well-established gas infrastructure including gas trade with neighbouring countries, strongly increasing biogas production, and an ongoing debate on future utilization of the gas and gas infrastructure.

2. Methodology

In this section, the general approach, the selected fuel supply pathways, data sources and assumptions are presented in brief. The various acronyms used in this paper are listed in Table 1.

2.1. General approach

The general process flow and major stages of the WTW evaluation are shown in Fig. 1. The activities are divided into two parts: WTT and TTW, or upstream and downstream, respectively. The WTW evaluations are the combined effect of the two parts, and the integration is made as shown in Eq. (1), Eq. (2), and Eq. (3).

To avoid redundancy and make it concise, the WTW evaluations are completed only for a number of selected pathways showing significant difference in terms of WTT energy and GHG emissions levels. The assumed functional units for the WTT and WTW evaluations are one MJ (or GJ) of final fuel and one driven distance (km), respectively.

The TTW evaluation[5] includes road and non-road transportation (passenger vessel) applications. Road transport pathways compare passenger car, LD, and HD conventional gasoline and diesel engine vehicles with three types of gas engine vehicles: port injection spark ignition (PISI), port injection dual-fuel (PIDF), and high pressure direct injection (HPDI) gas engines. Passenger vessel pathways compare low sulfur HFO- and MGO-propelled vessels with the aforementioned three types of gas engines.

Since the fuel economy is limited by vehicle class, traffic and road conditions, driving behaviour, and loading conditions, the real driving cycle considerably differs from the New European Driving Cycle (NEDC); hence, for emissions comparison, a holistic approach for TTW evaluations is to use type-approved data for conventional vehicles and real-world emission data for gas vehicles (as NGVs claimed to have lower emission levels anyways).

The evaluations have been done using a model developed in Excel comprising energy, GHG emissions, and air pollutant emissions evaluations. In most prior studies, air pollutant emissions were seldom evaluated, with the focus mostly on GHG emissions only. In this study, however, we have evaluated both the GHG and air pollutant emissions along the selected supply pathways, including methane leakage (associated with fuel supply) and methane slip (unburned methane from on-board combustion).

The WTW integration and the equations for energy, GHG emissions, and air pollutant emissions are:

$$WTW\left[\frac{MJ}{km}\right] = \left[WTT\left[\frac{MJ}{MJ_{\,finalfuel}}\right] - Credits\left[\frac{MJ}{MJ_{\,finalfuel}}\right]\right] * TTW\left[\frac{MJ_{finalfuel}}{km}\right] + TTW\left[\frac{MJ_{finalfuel}}{km}\right] = TTW\,[1 + WTT - Credits] \tag{1}$$

$$\begin{aligned} WTW\left[\frac{gCO_2eq}{km}\right] = &\left[WTT\left[[CO_2 + 30*CH_4 + 298*N_2O]\left[\frac{g}{MJ_{finalfuel}}\right] - Credits\left[[CO_2 + 30*CH_4 + 298*N_2O]\left[\frac{g}{MJ_{finalfuel}}\right]\right]\right]\right. \\ &* TTW\left[\frac{MJ_{finalfuel}}{km}\right] + TTW*\left[[\alpha CO_2 + 30*CH_4 + 298*N_2O]\left[\frac{g}{km}\right]\right] \end{aligned} \tag{2}$$

$$WTW\left[\frac{kg_{(CO,HC,NOX,PM)}}{km}\right] = WTT\left[\frac{kg_{(CO,HC,NOX,PM)}}{MJ_{finalfuel}}\right] * TTW\left[\frac{MJ_{finalfuel}}{km}\right] + TTW\left[\frac{kg_{(CO,HC,NOX,PM)}}{km}\right] \tag{3}$$

where *Credits* refer to the primary energy and GHG emissions savings associated with the use of digestate in place of synthetic fertilizer, and applies only for the biogas pathways; α is 1 (one) for fossil-fuel based pathways and 0 (zero) for renewable (biogas)-based pathways; and the coefficients 30 and 298 are the assumed CO_2 equivalent GWP of methane and nitrous oxide (N_2O), on a 100-year timescale, respectively. The total GHG emissions are the sum of each GHG in terms of CO_2 equivalent.

To capture possible variations in energy performance of outdated- and advanced technologies in the technology mix, we computed an upper (representing outdated technologies) and a lower (representing advanced technologies) values assuming a normal

[4] Compared to conventional fuel pathway's GHG emissions level, alternative pathways are referred to as impact inducing (higher emissions), impact reducing (lower emissions), or impact avoiding (negative emissions).

[5] Throughout the paper the term evaluation refers to the calculations of energy consumption and emissions in each pathway.

Table 1
Abbreviations.

Symbol	Description
CNG	Compressed Natural Gas
CRNG	Compressed Renewable Natural Gas
HDV	Heavy Duty Vehicle
HHV	Higher Heating Value
HPDI	High Pressure Direct Injection
IPCC	Intergovernmental Panel on Climate Change
JRC	Joint Research Center
LS-HFO	Low Sulfur Heavy Fuel Oil
LBG	Liquefied Biogas
L-CNG	Liquefied-Compressed Natural Gas
LDV	Light Duty Vehicle
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LRNG	Liquefied Renewable Natural Gas
LS-MGO	Low Sulfur Marine Gas Oil
NG	Natural Gas
NGVs	Natural Gas Vehicles
NMVOC	Non-Methane Volatile Organic Compounds
PIDF	Port-Injection Dual Fuel
PISI	Port-Injection Spark Ignition
PM	Particulate Matter
RNG	Renewable Natural Gas
TTW	Tank to Wheels
VRA	Vehicle Refueling Appliance
WTT	Well to Tank
WTW	Well to Wheel

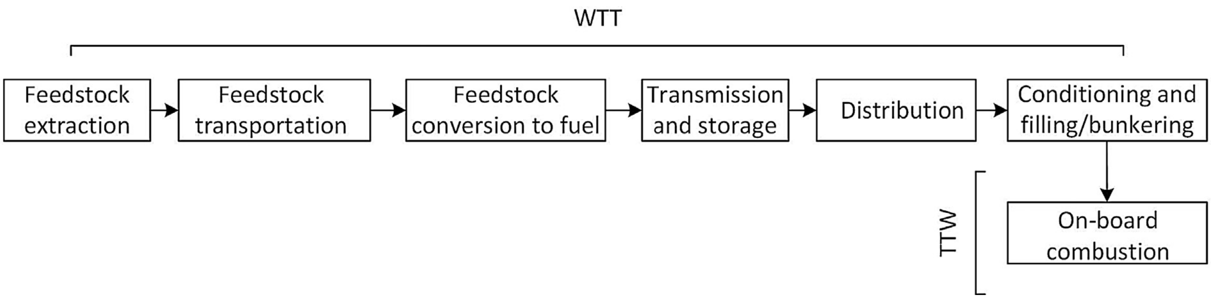

Fig. 1. Major stages of the WTW evaluation.

distribution and 95% confidence interval in each case. Similarly, to account for the impact of methane leakage on the overall GHG emissions in each pathway, we computed a 1% methane leakage sensitivity in each case.

2.2. Meta-analysis on WTT and WTW evaluations of alternative fuel vehicles

Lack of detailed data and standards for WTW evaluations, especially WTT evaluations, might result in different outcomes even for similar pathways, and hence, in misleading conclusions if results are compared directly. By grouping similar pathways based on their respective underlying critical assumptions, uncertainty maybe limited. Thus, we carried out a meta-analysis on the literature regarding WTW assessments of NGVs' fuel supply pathways covering different geographic scopes. Details are presented in Table 2.

In most pathways, the types of energy commodities and their origin, marginal substitutes of by-products, and fuel conversion efficiencies largely determines the overall energy saving and GHG emissions reduction potential of a specific pathway. That implies that the geographical setting is important since, for example, in terms of emissions factor, compared to an EU electricity mix, a US electricity mix differs considerably; the EU renewable share in electricity production is, on average, twice that of the USA (Curran et al., 2014; JRC, 2014).

LNG regasification involving shipping distances of 9300–11,500 km for Europe, USA, and South Korea showed similar WTW energy consumption and GHG emissions indicating the lower involvement of geographically-dependent energy commodities in the evaluation, like grid-electricity. Yazdanie et al. (2016) found the WTW energy and GHG emissions of AFV to be more dependent on the types of energy commodities used than the specific vehicle powertrain technology.

Table 2
The upstream (WTT) energy and GHG emissions of selected CNG and LNG pathways – a review.

Pathway	Final fuel	WTT (MJ/MJ_{fuel})	WTT (g CO_2/MJ_{fuel})	Geographic scope	Critical assumptions	Reference
EU-mix NG-2500 km	CNG	0.17	13	Europe		Joint Research Centre (JRC), 2014
Russia NG to EU-7000 km	CNG	0.29	22.6	Europe		
Middle east to EU-4000 km	CNG	0.21	16.1	Europe		
LNG regasification-10,000 km	CNG	0.26	21.3	Europe		
EU-shale gas	CNG	0.10	7.8	Europe		
LNG import-10,000 km	LNG	0.22	19.4	Europe		
Municipal organic waste	CBG	0.99	14.8	Europe	Fertilizer credit has not been assigned for digestate	
Wet manure	CBG	2.01	−69.9	Europe		
Whole maize	CBG	1.28	40.8	Europe		
Synthetic natural gas	CNG	1.06	3.3	Europe	(Renewable electricity and CO_2 from flue gas in power plant)	
LNG regasification-grid connected	CNG	0.26–0.28	28.9–33.4	South Korea	Imported LNG from Southeast Asia and Middle East. Assumed shipping distance about 9300 km	(Choi and Song, 2014)
LNG regasification-grid connected	CNG	–	23.05	California	Imported LNG from Borneo, Southeast Asia to LNG Terminal in Baja, CA. Assumed distance about 11,500 km	(Rosenfeld and Jackson, 2008)
Grid connected	CNG	–	9.93	California		
Land fill-biogas	CBG	–	−55.76	California		
On-site liquefaction	LNG	–	16.31	California		
LNG import terminal	LNG	–	18.72	California		
Land fill biogas liquefication and truck transportation	LBG	–	−59.46	California		
NG liquefaction at port/truck stop	LNG	0.12		Germany		(Wurster et al., 2014)
LNG import terminal (Qatar)-tank truck	LNG	0.25		Germany		
LNG import-bunker ship	LNG		74	Germany		
LNG import (Qatar)-inland ship-to-ship 500 km	LNG		74	Germany		
LNG import (Qatar)-truck to ship 5 km	LNG		75	Germany		
LNG import (Qatar)-truck to ship 500 km	LNG		76	Germany		
NG liquefaction at inland port	LNG		72	Germany		
NG liquefaction at truck stop	LNG		73	Germany		
Remote production and pipeline transportation-4000 km	CNG	0.182	14.9	Europe		(Alamia et al., 2016)
Remote production and shipping-10,000 km	LNG	0.23	16.52	Europe		
Thermal gasification based biomethane	CBG	1.02	21.5	Europe		
Thermal gasification based biomethane	LBG	1.07	26.22	Europe		
LNG Import terminals	LNG	–	16.88	Europe		(Arteconi et al., 2010)
Small-scale liquefaction	LNG	–	10.55	Europe		
Domestic NG-pipeline	CNG	–	6	Australia		(Beer et al., 2002)
Remote production and shipping-Import LNG	LNG	–	9	Australia		

Furthermore, in addition to the assumed gas yield, the marginal substitute of the by-products of biogas pathways largely impacts their energy consumption and GHG emissions advantages.

Based on the meta-analysis carried out, in this paper, special attention has been given to the assumptions involving the following activities:

- Amount of flared NG at gas fields.
- Long-range transportation distance: shipping, pipeline or truck/trailer.
- Type of process energy (electricity/thermal) and auxiliary energy sources (renewable/fossil).
- Type of feedstock (herbaceous/organic waste/manure).
- Process plant's conversion efficiency (gas yield) and marginal substitutes of by-products (credit for digestate).

2.3. Selected fuel supply pathways

The pathway selection has been done, mainly, based on a preceding state-of-the art review (Hagos and Ahlgren, 2017). Technology availability, economic feasibility, current trends in Denmark, the experience of earlier NGV adopters (like Italy, Germany, and Sweden), and the literature at large are also the basis for the selected pathways. The details of each pathway with description are given in Fig. 2 and Table 3.

Fig. 2 shows the major processes, activities and energy flows of the selected pathways in the WTT evaluation. The selected WTT pathways include a home filling facility or vehicle refuelling appliance (VRA) for private passenger car, public filling stations for all road vehicles, and bunkering facility for short-range passenger vessels. Based on their configuration, the filling stations are mainly classed into three, as shown in Fig. 2: (1) mother stations, which are connected to the NG grid through a pipeline; (2) daughter stations, which are not connected to the grid but are supplied with truck/CNG/CRNG[6] trailers from biogas upgrading facilities and mother stations; and (3) LNG/LRNG[7] stations supplied with truck/trailers from LNG/LRNG production facilities and LNG import terminals.

Table 3 presents the acronym, assumptions, and quantitative description of each selected pathways described in Fig. 2. The vehicle refuelling appliance (VRA), fast-fill mother station (CNGMF), and time-fill mother station (CNGMT) are connected to low-pressure NG distribution lines (4 bar), as shown in Table 1. Daughter stations (CNGD) are supplied with truck/trailer. A local biogas grid, if available, enables the connection of satellite digestion plants or small-scale raw biogas production plants with upgrading plants and makes use of economies of scale. However, in this study, we have considered only central biogas plants. The process pressure in upgrading plants is typically 6–7 bar, which is, considering pressure losses along the pipeline, enough to meet the 4 bar pressure requirement in a low distribution pipe. In fact, injecting into the distribution lines instead of the transmission lines would reduce the energy that would otherwise be used to transport the upgraded biogas down to the distribution lines. Therefore, VRA, CNGMT, and CNGMF pathways, in the WTT evaluation, would differ only on their filling station configuration and distance from the grid.

The daughter stations can be supplied by CNG tanks filled either at mother stations or at raw biogas upgrading plants, up to a maximum of 250 bar and distributed with truck/CNG trailer. The distance and number of stations served largely determines the distribution cost.

The LNG/LRNG filling stations supply only LNG/LRNG while in an L-CNG station both CNG and LNG are available. The stations are assumed to be skid-mounted.

For passenger vessel bunkering, ship-to-ship and truck-to-ship are the assumed bunkering methods. Small LNG carrier vessels (7500 m^3) and truck/trailer (60 m^3) are widely used for short-distance LNG transportation between north-west European ports and LNG terminals.

2.4. Data sources and assumptions

In this study, the primary data sources are Energinet (ENERGINET.DK, 2012, 2017), the Danish energy agency, IPCC Guidelines (IPCC, 2006), the literature, and the author's own analysis. The details of data sources and assumptions are discussed in brief in the order of: NG production, transmission, and distribution; local biogas production, upgrading and liquefication, and gas compression at filling stations; local gas distribution to off-grid or daughter stations; vehicles included in the TTW evaluation; methane leakage and methane slip; and type-approved and real-world vehicle emissions.

2.4.1. NG/LNG production and transport

The assumed domestic feedstocks are the Danish NG mix (as of 2016), organic municipal waste, and manure. Additionally, there are LNG imports via north-west European ports (GATE, Netherlands and Zeebrugge, Belgium) and local LNG/LRNG liquefaction plants.

In 2015, the annual NG production and domestic consumption in Denmark was 47.40 TWh and 29.16 TWh, respectively. The surplus was exported to Germany and Sweden. The offshore Danish gas fields are connected to an onshore gas treatment plant in

[6] Compressed renewable natural gas (CRNG) refers to a pipeline quality upgraded biogas.

[7] Liquefied renewable natural gas (LRNG) refers to a pipeline quality upgraded and liquefied biogas.

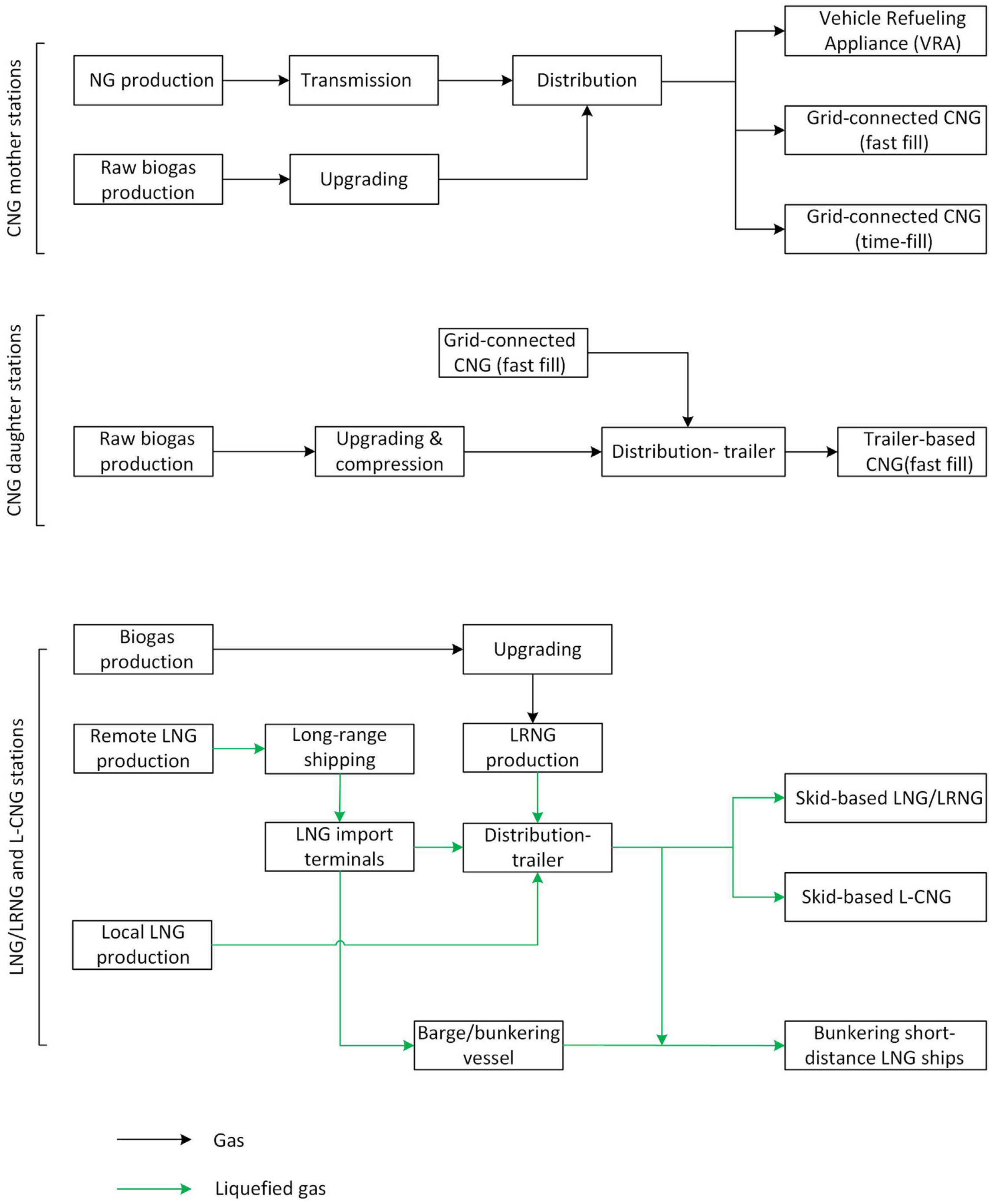

Fig. 2. Schematic diagram of the process flows for the upstream (WTT) evaluation. The filling/bunkering stations are classed into three: mother stations, daughter stations, and LNG/L-CNG stations.

Nybro with two high-pressure submarine pipelines, about 200 km in length (Danish Gas Technology Centre, 2016). After gas cleaning, the gas is distributed to various end users via a 925 km high-pressure (50–80 bar) steel transmission pipeline, and 2606 km steel (19–50 bar) and 15,612 km plastic (0.02–7 bar) distribution pipelines (Danish Gas Technology Centre, 2016). The transmission system is connected with two storage facilities with a total capacity of 1 billion Nm^3 (corresponding to 12,000 GWh) (Danish Gas Technology Centre, 2016). There are also injection compressors at the storage facilities with an energy efficiency of 0.03 kWh_e/Nm^3; the methane leakage of the compressors is assumed to be 20 $m^3/kW_{installed}/yr$ (IPCC, 2006). Energy consumption and GHG emissions associated with the gas production depend on the gas quality, field's location, and climate condition. Energy consumption, fugitive

Table 3
Selected pathways and process description.

Type	Pathway acronym	Final fuel	Pathway description
Mother stations	VRA	CNG	Danish NG mix, distributed through transmission and distribution pipes to grid-connected households/industries. The home-filling facility, called vehicle refuelling appliance (VRA), is assumed to be supplied with a low-pressure grid (4 bar)
	CNGMF CNGMT	CNG	Danish NG mix, distributed through transmission and distribution pipes to grid-connected filling stations. The station could be either a fast-fill (CNGMF) or time-fill (CNGMT) station connected with a low-pressure grid
	CRNGP-waste CRNGP-manure	CRNG	Raw biogas production from municipal organic waste (CRNGP-waste) and manure (CRNGP-manure), upgrading, and injection into the low-pressure grid (4 bar) through plastic pipes
Daughter stations	CNGD	CNG	The same process description as CNGMF pathway, but it represents daughter stations. CNG supplied to the station is assumed to be filled at mother station and transported with truck/CNG trailer
	CRNGD-waste CRNGD-manure	CRNG	Raw biogas production from municipal organic waste (CRNGD-waste) and manure (CRNGD-manure), upgrading and compression to 200 bar, and truck/CNG trailer distribution to fast-fill CNG filling station
LNG/LRNG stations	LNG	LNG	Remote LNG production, LNG sea transport to north-western Europe import terminals, distribution by truck/LNG trailer to skid-mounted LNG filling stations
	L-CNG	CNG/LNG	The same as LNG but at filling stations both LNG and CNG are available. Also, includes LNG vaporisation/compression to CNG at skid-mounted L-CNG
	LNG-STS	LNG	Remote LNG production, LNG sea transport to north western Europe import terminals, distributed by LNG bunkering vessel to bunkering facility at ports (storage tank); ship-to-storage (STS)
	LNG-TTS	LNG	The same process description as LNG-STS, but LNG assumed to be distributed by truck/LNG trailer to bunkering facility at ports (storage tank); truck-to-storage (TTS)
	LRNG-waste	LRNG	Raw biogas production from waste, upgrading, liquefaction, and local distribution by truck/LNG trailer to LNG filling stations
	LRNG-manure	LRNG	Raw biogas production from manure, upgrading, liquefaction, and local distribution by truck/LNG trailer to LNG filling stations

emissions, and flaring data at offshore gas fields, treatment plants and storage facilities are collected from (DONG energy, 2013a,b; Plejdrup et al., 2015).

NG transport in high-pressure and long-distance pipelines requires high-compression energy. The compressor station is assumed to be connected to the Danish power grid. For an 80 bar system, the specific energy consumption is assumed to be 0.269 MJ/ton-km (JRC, 2014). Methane leakage is assumed to be 0.13% of gas-transported/1000 km, but not more than the IPCC guidelines[8] in the transmission pipeline (2000 m^3/km/yr) (IPCC, 2006). The low-pressure distribution pipelines are parallel, at the same pressure; hence, no additional compression energy is required.

Currently, LNG is supplied to Danish customers from north-west European ports, mostly from the GATE terminal in Rotterdam, Netherlands and Zeebrugge, Belgium; the distance is about a 1900 km and a 1800 km round-trip by truck, respectively (Näslund, 2012). The storage capacity of the GATE terminal is 540,000 m^3 and that of Zeebrugge is 380,000 m^3 (King & Spalding LLP, 2015). Additionally, there is one LNG ferry bunkering facility at the port of Hirtshals with a 500 m^3 storage capacity; the source of the LNG is Norway. In addition to that, an LNG plant and bunkering facility is being constructed at the port of Frederikshavn (Bunker Holding, 2016; Näslund, 2012). For our study, we assumed the existing ports for LNG production and receiving terminal points in Denmark.

Energy consumption and GHG emissions associated with LNG production and loading terminals operation (0.09 MJ/MJ_{LNG} and 6.2 CO_2e/MJ_{LNG}) and long-distance shipping[9] to north-west European ports (10,000 km) (0.07 MJ/MJ_{LNG} and 4.8 g CO_2e/MJ_{LNG}) are taken from the JRC report (JRC, 2014). Additionally, at unloading terminals, a small amount of electricity is used for equipment operation, 0.001 MJ_e/MJ_{LNG}.

2.4.2. Raw biogas production and upgrading

Manure (cattle and pig slurry) and municipal organic wastes are the main biomass resources for biogas production in Denmark (Bundgaard et al., 2014). The raw biogas is mostly being used for power production in CHP plants, and only a small fraction is upgraded to pipeline quality and injected into the gas grid and/or used as a vehicle fuel. However, there is strong interest to increase the amount of upgraded biogas in the NG pipeline.

The digestate could potentially replace synthetic fertilisers. It is here assumed that the digestate actually is replacing synthetic fertiliser and, thus, in the evaluations a credit has been assigned both for the energy use and emissions associated with the fertiliser production (JRC, 2014).

Based on resource availability, the assumed manure composition is 40% cattle and 60% pig slurry. We assumed zero energy and emissions for municipal waste collection and transportation to digesters, as this should be done anyway (waste disposal). However, we have included the manure collection and digestate distribution. The weighted average transport distance and tractor vacuum storage capacity of 21 centralised biogas plants have been used to estimate the energy and emissions associated with the transport of

[8] The data sources are the International Gas Union (IGU) and main gas producers and exporters, including Russia and Algeria.
[9] The long-sea transport distance is assumed 10,000km, which is Arabian Gulf to Mediterranean or Nigeria to north-west Europe. The ship is assumed to be driven by LNG boil-off and HFO with an average speed of 36 km/h. The boil-off is assumed 0.15% per day.

Table 4
Typical gas yield and energy intensities for two biogas substrates (BISYPLAN, 2012; JRC, 2014; Jørgensen, 2009).

Substrate	Gas yield (m^3/kg-DM)	Heat ($MJ/MJ_{raw\ gas}$)	Electricity ($MJ_e/MJ_{raw\ gas}$)
Municipal organic waste[a]	0.43	0.0865	0.0622
Manure-cattle slurry	0.21	0.0962	0.0190
Manure-pig slurry	0.29	0.0962	0.0190

[a] The dry matter (DM) of typical Danish household waste, cattle slurry, and pig slurry are assumed to be 25%, 12%, and 9% respectively.

substrate to the central plant and digestate back to the farm. Hence, the tractor/vacuum tanker capacity is calculated to be 36 m^3 and transport distance 6 km (one-way) (Seadi, 2000).

The continuously stirred tank reactor (CSTR) is the most widely used biogas digester in Denmark. The process requires thermal energy (heat at optimal mesophilic temperatures (37 °C) or thermophilic temperatures (55 °C)) to enhance the digestion and electricity is used for pumps and other electrical appliances (Ward et al., 2008). The average thermal and electric energy usage for each substrate is given in Table 4. The source of the electricity is the Danish grid while the heat is assumed to be generated by an own raw gas-fired boiler with a 90% efficiency (LHV basis).

Typical raw biogas has a methane content of 50–65%, a Wobbe index of 7.8 kWh/Nm^3, and a relative density of 0.9. Thus, it needs to be upgraded to pipeline quality should it be injected into the grid and used as vehicle fuel. The current Danish gas standard limits are 13.9–15.5 kWh/Nm^3 for Wobbe index and 0.55–0.7 for relative density (EnergiNet.DK, 2017). A water scrubber (a matured and prevailing biogas upgrading technology) was chosen for this study due to its high market share (Bauer et al., 2013; Kadam and Panwar, 2017; Persson et al., 2006). The methane recovery rate is usually around 98%, with 2% methane loss (Bauer et al., 2013; Niesner et al., 2013). The upgraded biogas is assumed to have a 14.3 kWh/Nm^3 Wobbe index and 0.57 relative density with 98% methane content, and is assumed to comply with the Danish gas quality requirements. Studies have indicated the electrical energy consumption for the upgrading process to be: between 0.2–0.3 kWh/Nm^3 of raw biogas; for compression 0.10–0.15 kWh/Nm^3 operating at 6–8 bar; for water pumping 0.05–0.10 kWh/Nm^3; and for cooling (process water and compressed gas) 0.01–0.05 kWh/Nm^3 (Bauer et al., 2013; Niesner et al., 2013; Persson et al., 2006).

Since the low-pressure NG distribution lines are around 4 bar, the operating pressure of the upgrading plant, 6–8 bar, is sufficient to inject the upgraded gas into the gas grid available within the vicinity of the plant.

2.4.3. Small-scale biogas liquefaction

Liquefaction plants are matured technologies available in a wide range of capacities – small, medium, and large. The plant efficiency is very critical for the energy consumption and emissions related to liquefaction. Additionally, to avoid freezing and choking inside the pipeline system, the concentration of low boiling point compounds needs to be kept to the limit (Bauer et al., 2013). The produced LNG is stored on-site in cryogenic tanks at 3–10 bar. The propane pre-cooled mixed refrigerant, single mixed refrigerant (SMR), and the reverse Brayton cycle or expander process are the three most common types of liquefaction plants, based on their working thermodynamic cycle (Tuong-Van et al., 2016). The former is predominantly used for large-scale applications and accounts for more than 80% of global large-scale installations with 90.7% liquefaction efficiency[10] while the SMR and expander plants are suitable for small-scale applications with 89.4% and 88.2% liquefaction efficiency, respectively (Mintz et al., 2010).

The Lidköping LBG plant, based on a reverse nitrogen Brayton cycle, commissioned in 2012, is the first of its kind in Sweden with process capacity of 550 kg/h (765 Nm^3/h) LBG. The maximum processes electricity demand estimated to be 1.56 kWh/kg LBG. As opposed to the remote LNG plants, discussed in Section 2.4.1, the local LBG plants are assumed to use grid electricity as a power source. For our analysis, we used the Lidköping LBG plant's operation data due to its suitability for small-scale applications. At liquefaction plants, the gas leakage is estimated to be 0.05% of the gas throughput (IPCC, 2006).

2.4.4. Gas compression at filling stations

The compressor is the main energy-intensive equipment at filling stations. Mother filling stations are equipped with large compressors while daughter stations might have small boosting compressors. The compressors are assumed to use grid electricity as a power source. The actual power required is calculated from the ideal adiabatic compression work, as given in Appendix A.

The specific electrical energy consumption is calculated to be 0.19 kWh_e/kg. In Saadat-Targhi et al. (2016), using a flow modelling analysis, for fast-filling stations, the consumption was estimated to be 0.25 kWh_e/kg. For time-filling VRA stations, it was estimated to be 0.19 kWh_e/kg (Bang et al., 2014). The difference is partly due to the assumed pressure ratio, compression stage, and averaging the gas behaviour within the compression stages.

The Nordic average power plant efficiency and CO_2 emission intensity is assumed to be 0.45 (2.2 kWh/kWh_e) and 59 g CO_2/kWh_e, respectively (Nordic Energy Technology Perspectives 2016, 2016).

At filling stations, poorly maintained or unmaintained compressors are the main source of gas leakage (personal communication with experts). The methane loss during filling is insignificant. Thus, based on the IPCC guidelines, the methane leakage from the compressors is assumed to be 20 m^3/kW/yr (kW refers to the compressor's installed capacity).

[10] Liquefaction efficiency refers to the amount of natural gas converted into liquid; the unconverted gas usually compressed and recycled in the gas loop.

2.4.5. Local gas distribution system and filling stations

The local distribution system connects filling stations with fuel production plants and/or the NG grid. The mode of distribution is classed into four: a low-pressure polyethylene pipeline, CNG/CRNG swap body/truck, LNG/LRNG trailer/truck, and LNG carrier vessel.

A general distribution system sizing, based on total trip time to a station, model has been developed in Excel. Energy expended and emissions are calculated based on the annual fuel consumption and net gas delivered to a station.

A single swap body with steel CNG cylinders,[11] considering the back pressure inside the cylinders, could carry 1500 Nm^3 gas, and a truck/trailer combination could carry 3 swap bodies – one on the truck and two on the trailer.

The LNG truck/trailer and LNG carrier vessel are assumed to have a 60 m^3 and 7500 m^3 payload capacity, respectively. The total trip time[12] per day is the main parameter used to estimate the required number of truck/trailer combinations for each mode. As a reference, the distance between loading and unloading terminals is assumed to be 1 km for pipeline, 50 km for CNG/CRNG truck/trailer, and 950 km for LNG/LRNG truck/trailer and LNG carrier vessel (between GATE terminal in Rotterdam and Hirtshals port in Denmark).

Bunkering of LNG passenger vessels (ferries) could be done in three ways: (1) pipeline from nearby storage facility; (2) LNG trailer (truck-to-ship); and (3) barge/LNG carrier vessel (ship-to-ship). The LNG trailer and LNG carrier vessel options are more flexible and suitable for small-scale application (Näslund, 2012); hence, both have been assessed in this study as the market in Denmark is in its infancy.

At filling stations, based on the EU standard prEN 13,638 (still daft), CNG vehicles shall be filled up to a nominal pressure of 200 bar at 15 °C; the lower the temperature, the higher would be the nominal pressure and vice versa, but the maximum limit is 260 bar. The high-pressure gas in the transmission line (about 80 bar) is fed to the low-pressure distribution lines (4 bar) via trunk lines (about 40 bar). Thus, given the well-established gas network in Denmark, we have assumed all grid-connected CNG stations to be supplied with the 4 bar distribution lines. The filling station's capacity is assumed to be 1800 Nm^3/day.[13]

2.4.6. Vehicles included in TTW evaluation

NGVs are commercially available alternative fuel vehicle technologies. The fuel source could be NG and/or RNG. To provide a longer driving range for NGVs, the gas could either be compressed to about 200 bars and stored in high-pressure tanks, or cooled to −162 °C at atmospheric pressure and stored in highly insulated cryogenic tanks. It is then labelled as either compressed natural gas (CNG) or liquefied natural gas (LNG). The three state-of-the art gas engine technologies are PISI, PIDF, and HPDI engines.

The PISI gas engine works on a lean-burn Otto cycle and 100% gas, with a spark-plug initiating ignition like any other conventional gasoline engine. For HDV applications, since the PISI engine is built on a re-configured diesel engine running on Otto cycle, it has a lower compression ratio and volumetric efficiency, and, thus, a lower cycle efficiency (about 35%) in comparison to conventional diesel engine. Additionally, the tailpipe environmental advantages of NG, as a clean burning fuel, are offset by the lower efficiency of PISI engines.

The PIDF engine works on both diesel and gas; 50–60% gas (on energy basis). In gas mode, the engine works on Otto cycle with pilot diesel injection to initiate ignition and on a conventional diesel cycle in diesel mode. Additionally, the engine is usually optimised for gas operation and exhibits similar efficiency to conventional diesel engines (about 43%). However, transient driving cycle or frequent start-stop in urban driving at lower load and methane slip due to poor combustion at lower load are shortcomings that might offset the higher efficiency advantages, which are preferable in long-haulage transport. PIDF engines showed compliance with Euro V standard but their Euro VI homologation status is not clearly known.

The HPDI gas engine works on the diesel cycle with 90–95% gas; a small amount of diesel is used to assist ignition and avoid ignition delay, as NG has a lower cetane number, and hence, longer ignition delay. As opposed to PISI and PIDF, in a HPDI engine, the gas is injected directly into the cylinder at high pressure (about 300 bar), with either an on-board LNG pump or CNG compressor. The main advantage of a HPDI engine over a PIDF or PISI engine is its ability to knock resistance at higher loads and cover a wider power range like a conventional diesel engine (Hegab et al., 2017). This makes the HPDI engine suitable for long-haulage heavy-duty transport applications, and, potentially, it could displace more than 95% of its diesel consumption. Nevertheless, due to its harsh combustion process (high pressure and temperature), NOx emissions are usually higher than in PISI and PIDF engines (Hegab et al., 2017). Recently a company announces the commercialisation of its Euro VI compliant HPDI LNG Trucks (dieselNet, 2017).

In this study, as briefly discussed earlier, the use of LNG/LRNG is restricted to HDV and passenger vessel classes, due to the limited cargo space.

In PIDF and HPDI engines the diesel substitution (on energy basis) is assumed to be 60% and 95%, respectively. In addition, we used the type approved fuel economy in all cases. We assumed medium class brake-power (conventional passenger cars and LDVs 81 kW and for HDVs 209 kW), and fuel economy 19 L/km (for conventional passenger cars and LDVs) and 31 L/100 km for HDVs. For gas vehicles, the assumed fuel economy is 3.74 kg/100 km (for conventional passenger cars and LDVs) and 28 kg/100 km for HDVs. For short-range passenger vessels, the fuel economy was estimated assuming a vessel capacity of 600 passengers as given in Appendix B.

[11] Use of composite cylinders, instead of steel cylinders, could potentially double the swap body transport capacity; however, this would be at the expense of the high added cost of the composite material.

[12] The speed of the truck/trailer and cruising speed of the LNG carrier vessel are assumed 50 km/h and 20 knot (37 km/h), respectively.

[13] Most filling stations in smaller cities in Sweden sell between 400 and 500,000 Nm^3 gas per annum. However, to reach break-even, they need to sell more than 600,000 Nm^3 (personal communication).

2.4.7. Methane leakage and methane slip

The global warming potential (GWP) of methane is 25–36 times stronger than CO_2 on a 100-year timescale. Thus, a small fraction of methane leakage[14] might offset the overall climate advantages of gas in transport, and needs to be accounted for carefully. Accordingly, methane leakage from NG production and processing facilities (0.2% of net annual gas production), transmission pipeline (2000 m^3/km/yr), and compressor stations (20,000 m^3/MW/yr – MW referring to compressor installed capacity), and distribution pipelines (1000 m^3/km/yr) are all accounted for and calculated based on the IPCC guidelines (IPCC, 2006).

We have also accounted for methane leakage during bunkering. Bunkering leakages are mainly due to boil-off, purging from fuel hoses right after filling the vessel, venting of displaced vapour when filling a storage tank, and flash losses created during pre-cooling fuel lines prior to filling or fuel transfer. The level depends on the bunkering facility and its location relative to the source. It could range between 0.13 and 0.22% of LNG fill (mass basis) (Corbett et al., 2015). Bunkering close to the source has the advantage of enabling boil-off recovery. Currently, flaring with 95% efficiency is the best practice (Corbett et al., 2015).

In addition to the routine bunkering leakage, non-routine leakage should also be incorporated. This might happen a few times in a year due to accidents or equipment failures, but could result in a considerable increase in GHG emissions. However, it is difficult to make a reasonable assumption without historical data, and, thus, it is not considered in this study. The same is true for gas blow-off during maintenance of transmission and distribution pipelines or unforeseen circumstances.

Methane slip (or un-oxidised methane emissions) usually occurs due to low temperatures in the three-way catalyst at lower loading and transient driving cycles, such as driving in metropolitan areas. Thus, under real driving cycles, the methane slip would be higher in urban driving than rural driving. Based on the literature review, an assumed value has been used for each case. The details are given in Appendix B.

2.4.8. Type approved and real-world vehicle emissions

For conventional vehicles, we have chosen to use the type approved Euro 6 limit for passenger car and LDV classes and Euro VI for HDV class, while for NGVs, we have used chassis dynamometer measured emissions data (Natural & bio Gas Vehicle Association (NGVA) Europe, 2016). The data is shown in Appendix B.

For conventional passenger vessels, we have chosen to use the MARPOL Annex VI NO_x and sulfur limit in ECAs (the binding limits for a passenger vessel cruising in ECAs are fuel sulfur content and NOx emissions), while for LNG passenger vessels cruising in ECAs, we have chosen to use literature-based real-world emissions data. The data is shown in Appendix B.

3. Results and discussions

Based on the assumptions discussed briefly in Section 2, the WTW energy and emissions of the selected pathways have been investigated. The results are presented in this section. The pathways are evaluated in a Danish gas (natural gas/upgraded biogas) context, represent 2016s grid gas composition, and are based on mature energy technologies and possible credits for biogas-digestate (Section 2.4.2).

The results are interpreted in relation to reference pathways. In Section 3.1, for the upstream evaluations (WTT), the gasoline pathway is used as a reference. In Section 3.2 and onwards, for road-transport applications, a Euro 6 gasoline vehicle is used as reference vehicle for passenger car and LDV classes while a Euro VI diesel vehicle is used for the HDV class. For maritime transport applications, a MARPLO Annex VI compliant LS-HFO passenger vessel is used as reference vessel.

Compared to their respective reference pathway's GHG emissions level, alternative pathways are referred to as impact inducing (higher emissions), impact reducing (lower emissions), or impact avoiding (negative emissions).

3.1. WTT energy consumption and GHG emissions

Figs. 3 and 4 shows the WTT energy consumption and GHG emissions (by type of GHG) associated with the final fuels (CNG/CRNG/LNG/LRNG) production at filling stations and bunkering sites, for each pathway, respectively. The reference gasoline and diesel pathways are from (JRC, 2014). The cumulative uncertainties of each pathway are shown by error bars.

The CNG pathways show similar energy demands (of 0.09 MJ/MJ_{fuel}), considerable lower than the gasoline/diesel (0.18/0.2 MJ/MJ_{fuel}), CRNG-manure (0.81 MJ/MJ_{fuel}), and CRNG-waste (1.31 MJ/MJ_{fuel}) pathways. The small energy demand differences between the CNG pathways are due to similarities in filling stations' configuration and low gas distribution energy demand. In terms of GHG emissions, compared to the reference gasoline pathway, CNG pathways showed 74–79% lower GHG emissions, mainly due to long-range crude oil transportation. In comparison with similar CNG pathways (JRC, 2014) for long-distance NG transport (2500 km), our results showed 78% lower GHG emissions due to the short Danish NG transmission pipeline (900 km), lower share of flared NG at offshore gas fields, and lower CO_2 intensity of compression at filling stations. The impact of gas transport distance on the WTW energy and GHG emissions is demonstrated in Shen et al. (2012).

Compared to the gasoline reference pathway, the renewable (CRNG-manure and CRNG-waste) pathways show higher expended energy, 0.63 and 1.13 MJ/MJfuel higher, respectively, but are found to be impact avoiding in terms of GHG emissions. The CRNG-manure pathway is both less energy intensive and more impact avoiding than the CRNG-waste pathway due to better digestate

[14] Methane leakage and methane slip are general terms used to refer to methane loss related to fuel supply and on-board combustion, respectively.

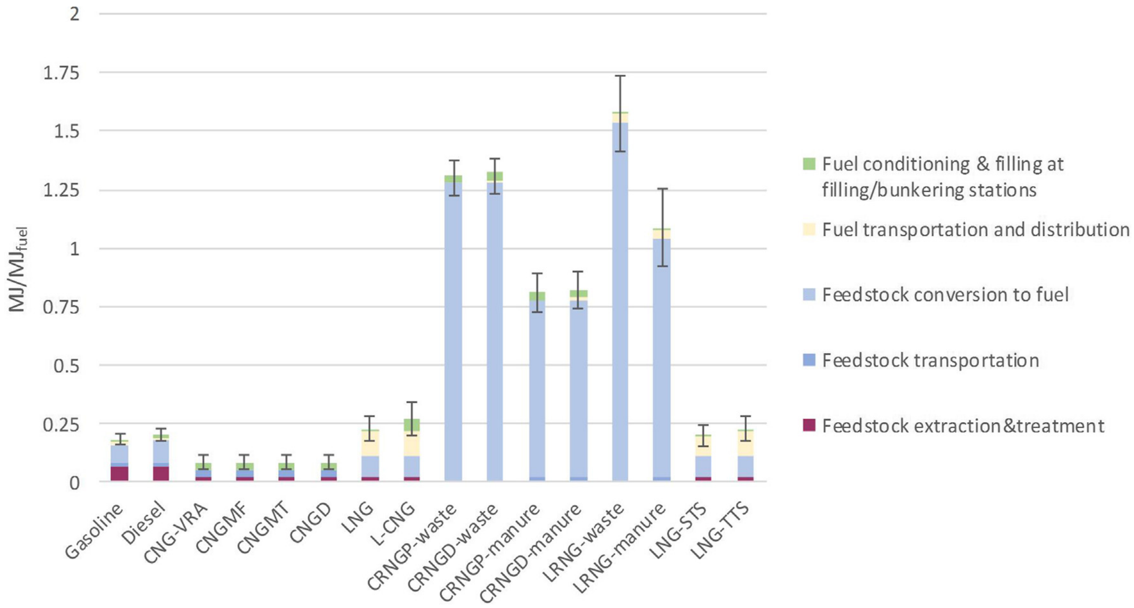

Fig. 3. WTT energy consumption of the selected pathways. It shows the primary energy expended to produce a MJ of the final fuel, excluding the energy content of the fuel itself. The error bars in each pathway show the cumulative uncertainties in energy performance of outdated and new technologies.

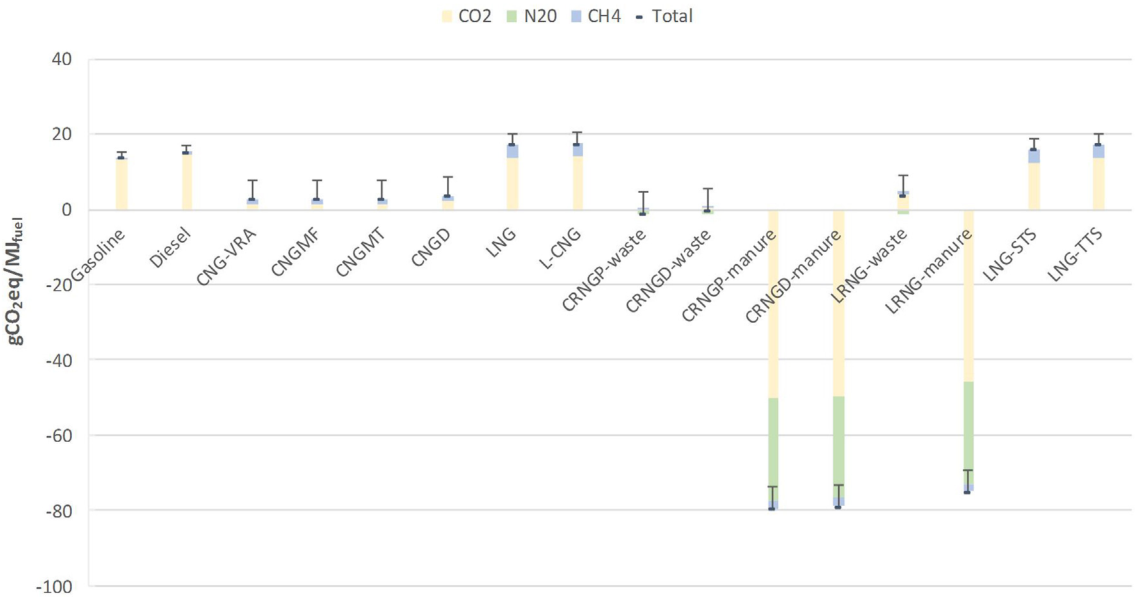

Fig. 4. WTT GHG emissions (by type of GHG) of selected pathways. The upper error bar in each pathway shows the total GHG emissions when the assumed methane leakage increases to 1%.

quality and increased fertiliser substitution.[15] Without the assigned credits, both renewable pathways would instead be impact reducing (3.63 and 2.76 g CO_2eq/MJ_{CRNG} for the CRNG-manure and CRNG-waste pathways, respectively). This effect is stronger on the manure-based pathways than on the waste-based pathways.

Compared to gasoline pathway, the LNG and L-CNG pathways show both a slightly higher increment both in terms of energy expended and GHG emissions owing to the remote production, added liquefaction, and long-range transport energy demand and for L-CNG also, pumping to high pressure (200 bar) and LNG vaporisation to CNG Since transportation constitutes a large portion of the

[15] For the waste digestate, the calculated credits for CO_2, CH_4, and N_2O emissions, in terms of CO_2eq, were 2.34, 0.136, and 1.25 g CO_2eq/MJ_{CRNG} while for the manure digestate calculated to be 53.2, 2.96, and 27.08 g CO_2eq/MJ_{CRNG}, respectively.

total energy and GHG emissions, as shown in Figs. 3 and 4, local LNG production only results in a marginal increment in energy and emissions over the CNG pathways. Because of this we did not consider such a pathway here, to avoid redundancy.

There is an insignificant difference between the CNGMT and CNGD pathways as energy expended for distribution is very small and not enough to make a noticeable difference between pipeline and truck/trailer gas distribution.

It is worth comparing our WTT results with prior studies. For example, in JRC (2014), WTT energy and GHG emissions for CNG pathways are estimated to be between 0.17–0.29 MJ/MJ_{CNG} and 13–26 g CO_2eq/MJ_{CNG}, for an assumed 2500–7000 km long-distance pipeline transport. The high compression energy required for this long-range transport distance means higher expended energy and GHG emissions. For liquid-manure and organic waste, the expended energy and GHG emissions were estimated to be 0.99 and 2.01 MJ/MJ_{CRNG} and −69.9 and 14.8 g CO_2eq/MJ_{CRNG}, respectively. The assumptions on digester gas yield and the cattle/pig slurry proportions and compression energy CO_2 intensity at filling stations are the main sources for the discrepancy. These emphasise the need for a localised WTW study, such as this study. The fact that the GHG emissions of the waste pathway in JRC (2014) is higher than the reference pathway is because credit has not been assigned; instead, the digestate was assumed to be dumped. Looking at Fig. 4, the contribution of each GHG (CO_2, CH_4, and N_2O) for the total GHG emissions on a 100 year time scale, CO_2 emission prevails in all pathways, and CH_4 constitutes a small fraction while N_2O is almost zero except the avoided N_2O emission due to synthetic fertiliser substitution in the renewable-based pathways. However, if credit were not assigned for the digestate, both renewable-based pathways would be impact reducing pathways instead of being impact avoiding.

The upper error bars in Figs. 3 and 4 show the increase in total GHG emissions assuming a methane leakage level of 1% (instead of (0.2–0.5%)). An assumed 1% methane leakage reduce the GHG emissions advantages by 39–41% in the CNG pathways, 26–48% in the LNG pathways, and 14–37% in the renewable-based pathways indicating that methane leakage is one of the most critical parameters highly impacting the GHG emissions profile of gas in any application.

3.2. WTW energy consumption and GHG emissions

This section presents the overall WTW energy expended and GHG emissions of passenger car and LDV classes, respectively. As explained in Section 2.1, the WTT fuel supply pathways are integrated with the TTW energy and emissions of the respective vehicles.

In terms of energy expended, as shown in Fig. 5, on average, both CNG pathways showed a 3% reduction, while the renewable pathways showed an increment of 108% and 62% for waste- and manure-based pathways, respectively. The assumed energy performance uncertainty has little effect on both the CNG and renewable based pathways, mainly due to the lower energy demand per km travel of the passenger and LDV classes.

For passenger cars and LDV classes, all gas pathways are GHG impact reducing compared to the reference pathway with, on average, a 27% reduction while the renewable pathways are impact avoiding with a 101% and 196% GHG emissions reduction for the waste- and manure-based pathways, respectively (Figs. 5 and 6).

The WTW GHG emissions are shown in Fig. 6. Compared to the reference pathway, all gas pathways found to be impact reducing with, on average, a 27% reduction, while the renewable pathways are found to be impact avoiding with a 101% and 196% GHG emissions reduction, for waste- and manure-based pathways, respectively. The higher being for manure-based pathway due to the high nutrient content of manure digestate over organic waste, hence, higher synthetic fertiliser substitution credit. However, when the methane leakage increases to 1%, the impact reducing effect of the CNG pathways reduces by 23%, and the impact avoiding effect by 3.5–7% for the renewable-based pathways as shown by the upper error bars in Fig. 6.

Figs. 7 and 8 shows the results for the HDVs. The relatively higher energy demand per km travel of the HDV class makes the energy intensive renewable-based pathways even more energy intensive as shown in Fig. 7. The increments range in between 2–26%

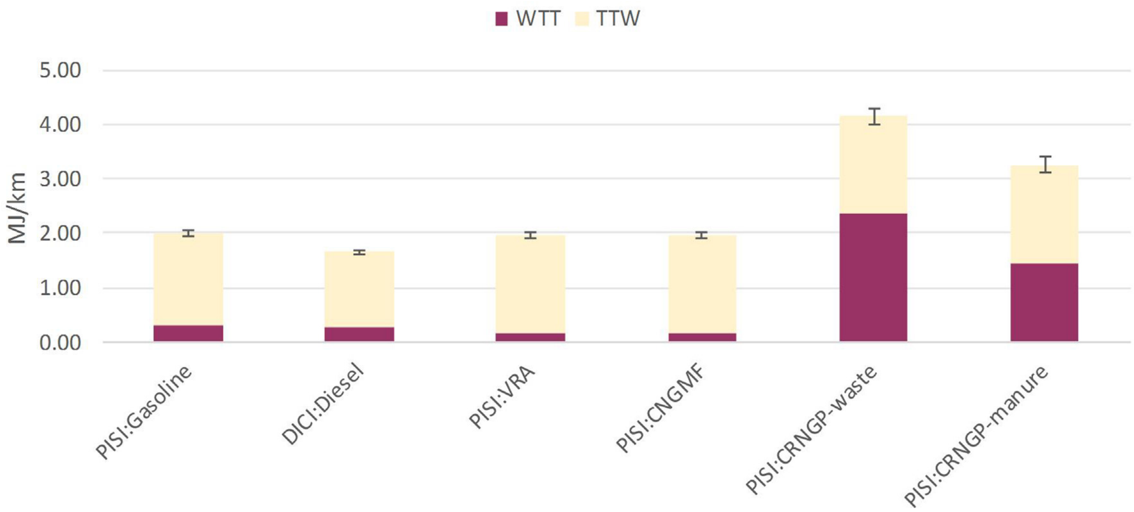

Fig. 5. WTW energy consumption of selected pathways for passenger car and LDV classes.

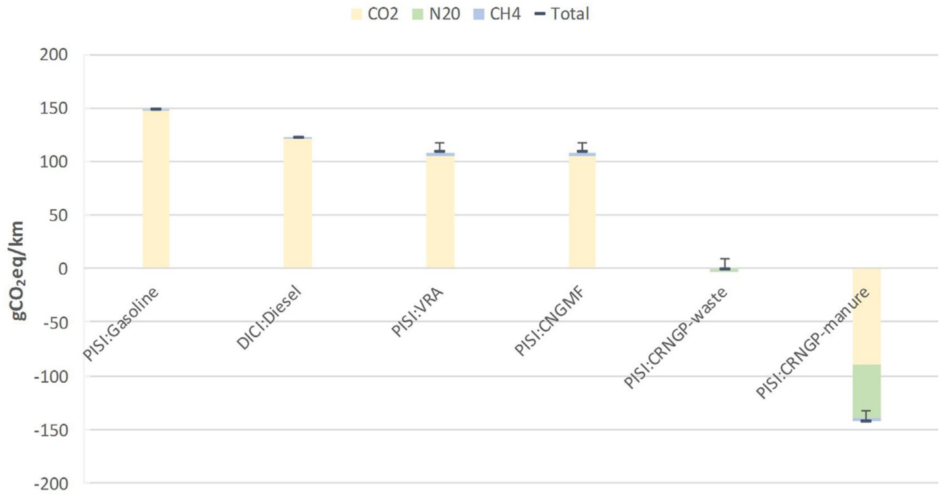

Fig. 6. WTW GHG emissions (by type of GHG) of selected pathways for passenger car and LDV classes.

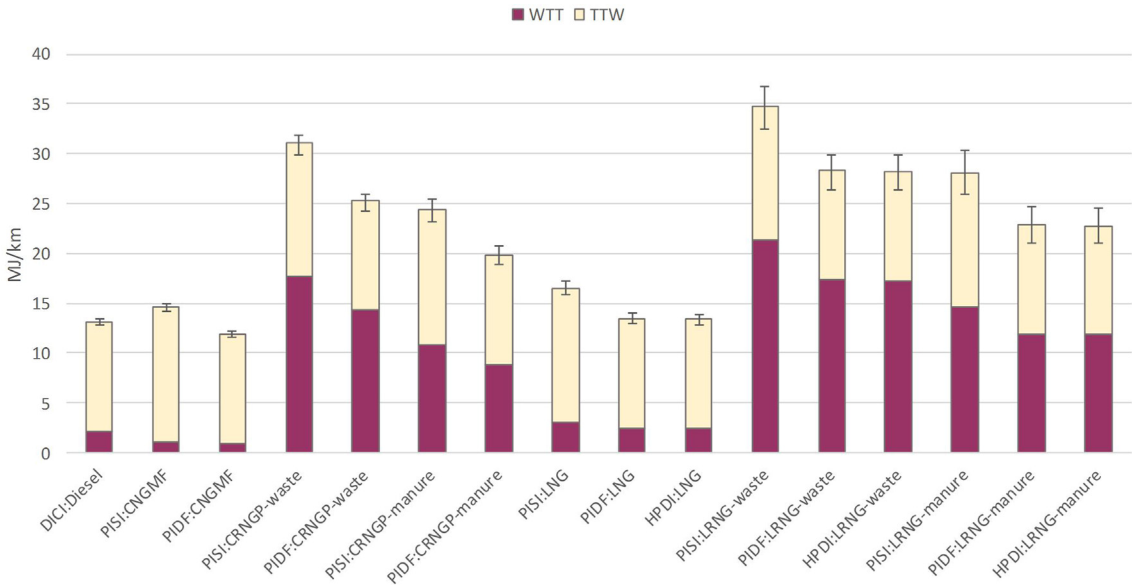

Fig. 7. WTW energy consumption of selected pathways for HDV class.

in LNG pathways and 51–166% in renewable-based pathways. Only the PIDF: CNGMF pathway showed a 9% lower energy expended per km travel than the reference pathway.

All gas pathways except two pathways (PISI: LNG and PIDF: LNG) are impact reducing due to the WTT impact inducing effect of the imported LNG (see Fig. 3). The level of emissions reduction largely depends on the methane slip and fuel economy of the specific vehicle. Compared to the reference pathway, PISI: CNGMF and PIDF: CNGMF show 17% and 15% lower GHG emissions, respectively; due to (1) the methane slip of the PIDF engine offsets the reduced CO_2 emissions associated with diesel substitution, and (2) even though the PISI gas engine has a lower fuel economy, its lower methane slip outweighs or level off the GHG emissions advantage of PIDF engine; its impact reducing effect reduces by 29–42% when the assumed methane leakage increases to 1% as show by the upper error bars.

The HPDI engine, apart from its high diesel substitution and GHG emissions advantages, could also alleviate the operational challenges of PIDF engines, and reduce methane slip and hydrocarbon emissions in general.

The manure-based pathways, in most cases, are impact-avoiding. However, looking at LNG-manure: PISI, LNG-manure: PIDF, and LNG-manure: HPDI pathways, PIDF engine converts the impact-avoiding ability of the PISI engine into impact-inducing while the HPDI engine substantially reduces its impact avoiding effect.

The CO_2 emission impacts dominates the HDV GHG emissions for all pathways, but there is also a substantial amount of avoided N_2O emissions avoided N_2O emission due to synthetic fertiliser substitution in the renewable-based pathways (see Fig. 8). The

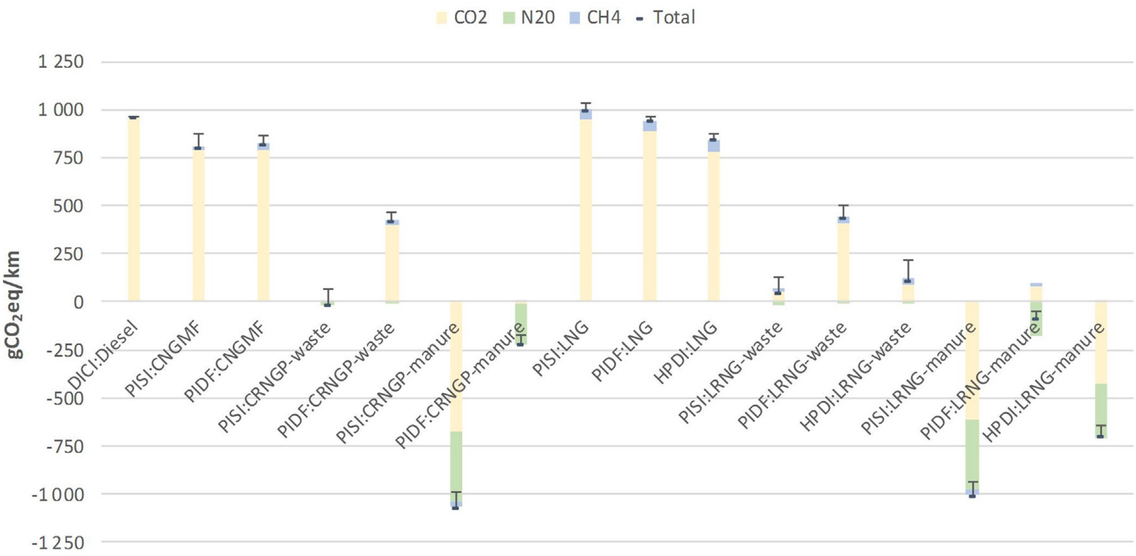

Fig. 8. WTW GHG emissions (by type of GHG) of selected pathways for HDV class.

contribution of methane (CH_4) is mainly noticeable in the PIDF engine pathways, mostly originating from methane slip.

For a passenger vessel operating in ECAs (Fig. 9), compared to the reference pathway, the LNG pathways show a 7–26% increment in expended energy, but noticeably higher, 81–191%, in renewable-based pathways, owing to its lower efficiencies.

The higher fuel consumption, even more than for HDVs, contributes a lot to a higher GHG emissions reduction per unit km travel, if any, as shown in Fig. 10. Except in the manure-based pathways, PISI and PIDF engines found to be impact inducing. HPDI showed a marginal reduction (7–9%) and found to be impact reducing in all cases; the effect is more pronounced in LRNG-manure, and found to be impact avoiding with a 176–191% reduction. Additionally, on a WTW energy basis, truck-to-ship (TTS) tends to have a marginal increase (2%) over ship-to-ship bunkering, as the energy consumption and emission of the LNG carrier are both noticeably lower.

Evaluating the contribution of each GHG on the total emissions, owing to the higher fuel consumption in the passenger vessel case, and hence, the methane slip, the contribution of methane (CH_4) is noticeably higher in PISI and PIDF engines. It is worth mentioning that the total GHG emissions per km travel is highly dependent on the fuel economy of the assumed vessel, and care should be given when comparing the results with similar prior studies.

3.2.1. Methane slip sensitivity analysis

To account for the impact of methane slip on the WTW GHG emissions of maritime transport, four sensitivity cases were

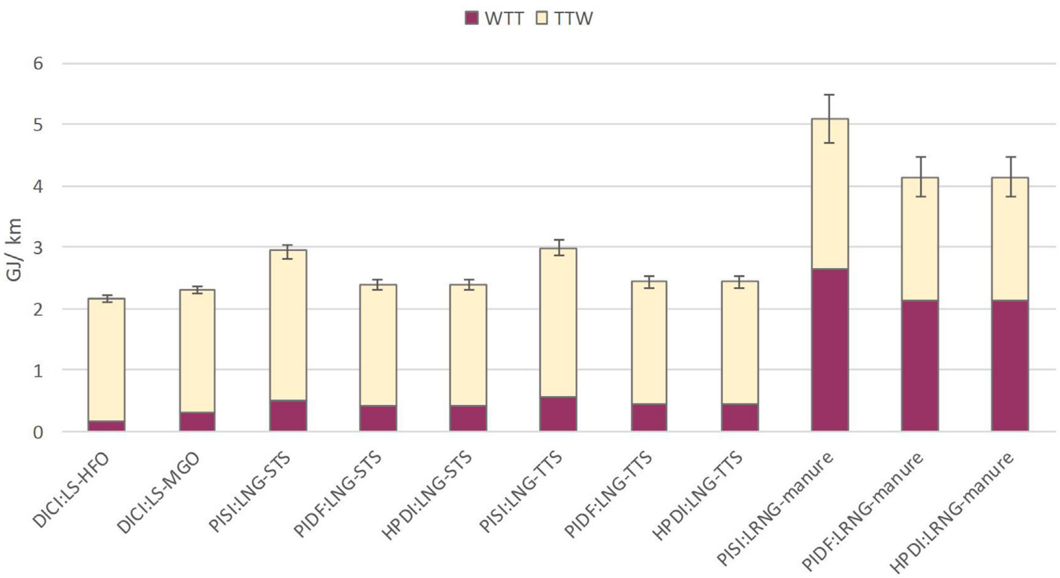

Fig. 9. WTW energy consumption of selected pathways for maritime transport application (passenger vessel).

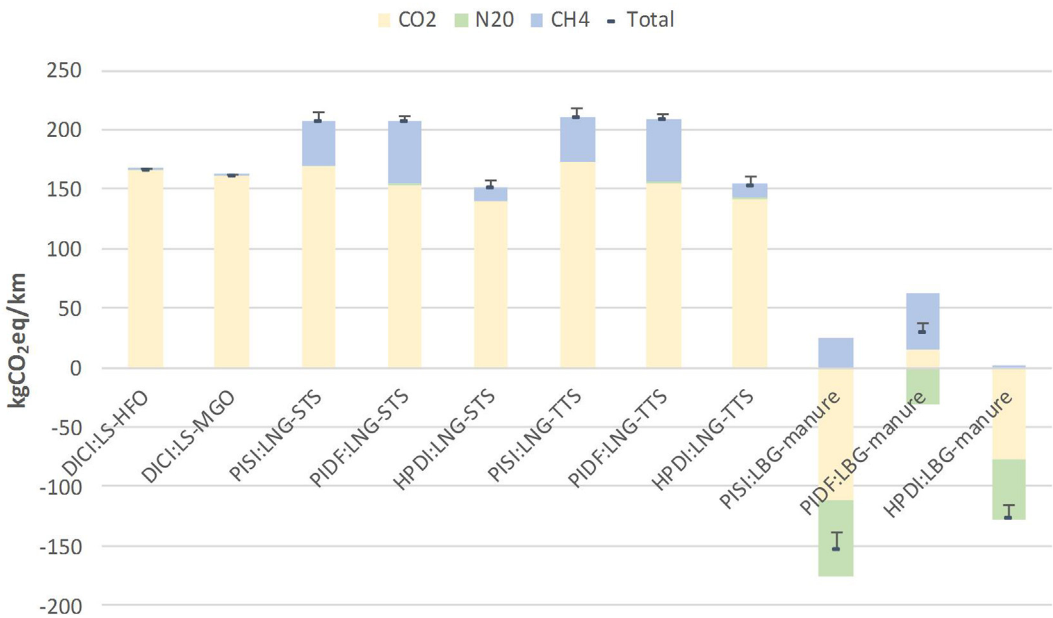

Fig. 10. WTW GHG emissions (by type of GHG) of selected pathways for maritime transport application (passenger vessel).

formulated; 0%, 1%, 1.5%, and 2% methane slip. Fig. 11 shows the impact of methane slip on the overall GHG emissions of selected pathways. The result shows that a 1% methane slip, on average, would results in 8.5%, 4.7%, and 8% increase in net GHG emissions in PISI, PIDF, and HPDI LNG vessels, respectively; these largely attribute to the assumed LS-HFO substitution levels of the three gas engines. The result is in line with Corbett et al. (2015).

Compared to the reference LS-HFO vessel, in PIDF and HPDI LNG vessels, a 1.5% and 1% methane slip, respectively, is enough to completely offset their respective net GHG emissions advantage. In HPDI LNG vessels, the reported methane slip is about 0.4%, and not big enough to offset its net advantage. But, in PISI and PIDF LNG vessels, the reported methane slip is about 2.86%, and hence, found to be impact inducing pathways.

Between 2010 and 2016, on average, a 50% methane slip reduction was noted for Norwegian PISI and PIDF LNG vessels due to better engine technology; from 4.4% to 2.3% and 8% to 4.1%, respectively (Stenersen and Thonstad, 2017), showing that with, advancing technology, there are opportunities for further reduction of the methane slip associated with gas engines.

3.3. WTW air pollutant emissions

For the passenger cars and LDVs, there is a substantial WTW air pollutant emissions advantage of using CNG in comparison to gasoline and diesel (Fig. 12). Since this is consistent between the pathways it suggests that on-board combustion is the major source of air pollutants in all pathways. The type of aftertreatment system deployed largely determines the level of air pollutant emissions in both stationary and mobile applications. It was noticed that the WTT air pollutant emissions is insignificant (and hence not shown in Fig. 12), and a large part of the WTW emissions originates from on-board combustion (TTW). The small fraction from upstream (WTT) is related to feedstock and/or fuel transportation and stationary combustions.

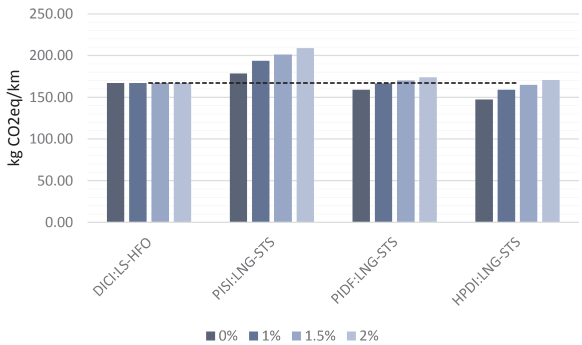

Fig. 11. Impact of methane slip on the overall (WTW) GHG emissions benefit of each selected pathway for maritime transport application (passenger vessel). The assumed cases are: a 0%, 1%, 1.5%, and 2% methane slip.

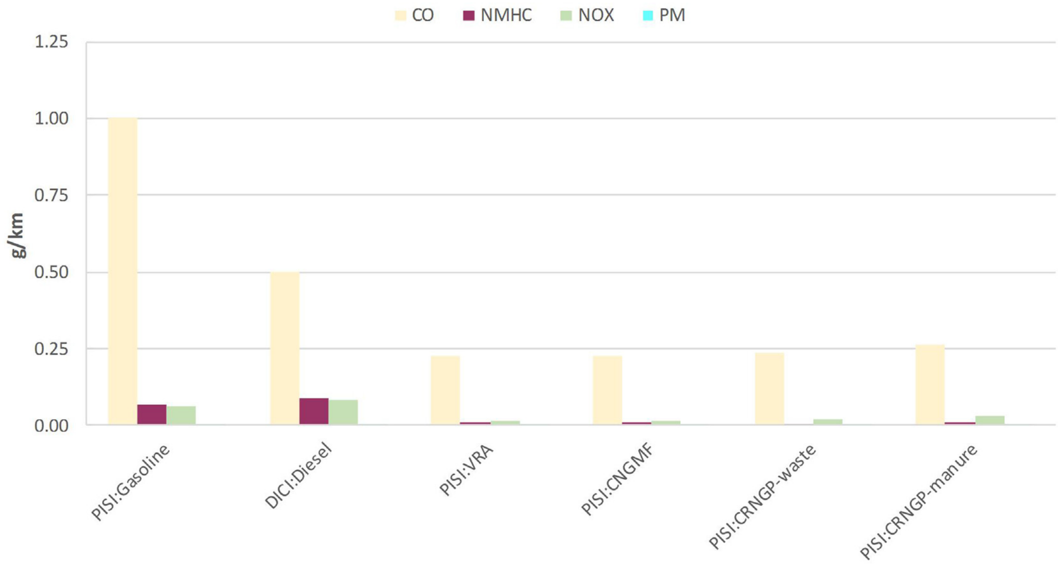

Fig. 12. WTW air pollutants emission of the selected pathways for the passenger car and LDV classes.

Given the lower WTT air pollutants emission in all CNG and CRNG pathways, passenger car and LDV showed substantial emissions reduction.

Fig. 13 shows the WTW air pollutant emissions per km travel for HDVs. The results are compared to Euro V and Euro VI compliant vehicles. Compared to the Euro VI reference vehicle, only the HPDI gas engine vehicle shows a substantial reduction in CO and NMHC emissions but slightly higher NOx emissions. There exist a slightly higher NOx and CO emissions even from Euro VI gas vehicle, questioning the true advantages of HD gas vehicles in terms of regulated emissions. This is because of the stringent Euro VI emission standard. Nevertheless, compared to the Euro V compliant vehicles, their advantage in terms of NOx and NMHC emissions reductions is significant. The performance of the PIDF HDV in all pathways found to be poor, and results in high NOx and NMHC emissions. It is worth mentioning that the data was based on a Euro V compliant PIDF truck.

Fig. 14 shows the WTW air pollutant emissions per km travel for the passenger vessel class. The MARPOL Annex VI convention covers only the sulfur limit and NOx, and is not binding for PM, CO, CH_4, and other hydrocarbons. The assumed passenger vessels, both conventional and LNG vessel, cruises only in emission control areas (ECAs). With this understanding, as shown in Fig. 14,

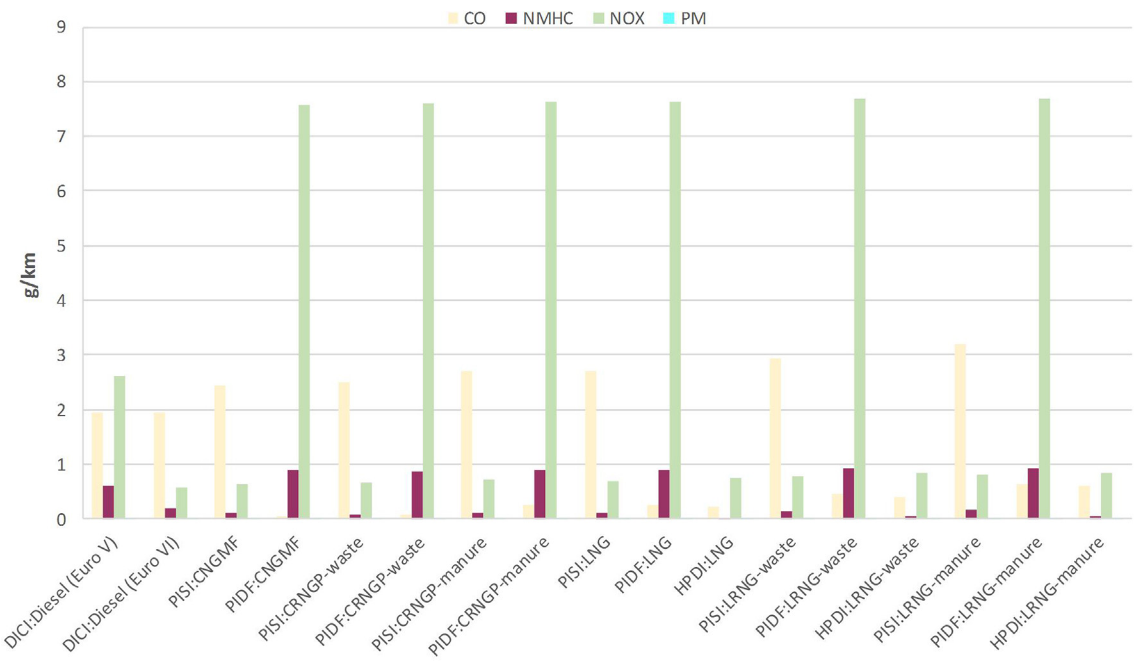

Fig. 13. WTW air pollutants emission of the selected pathways for HDV class.

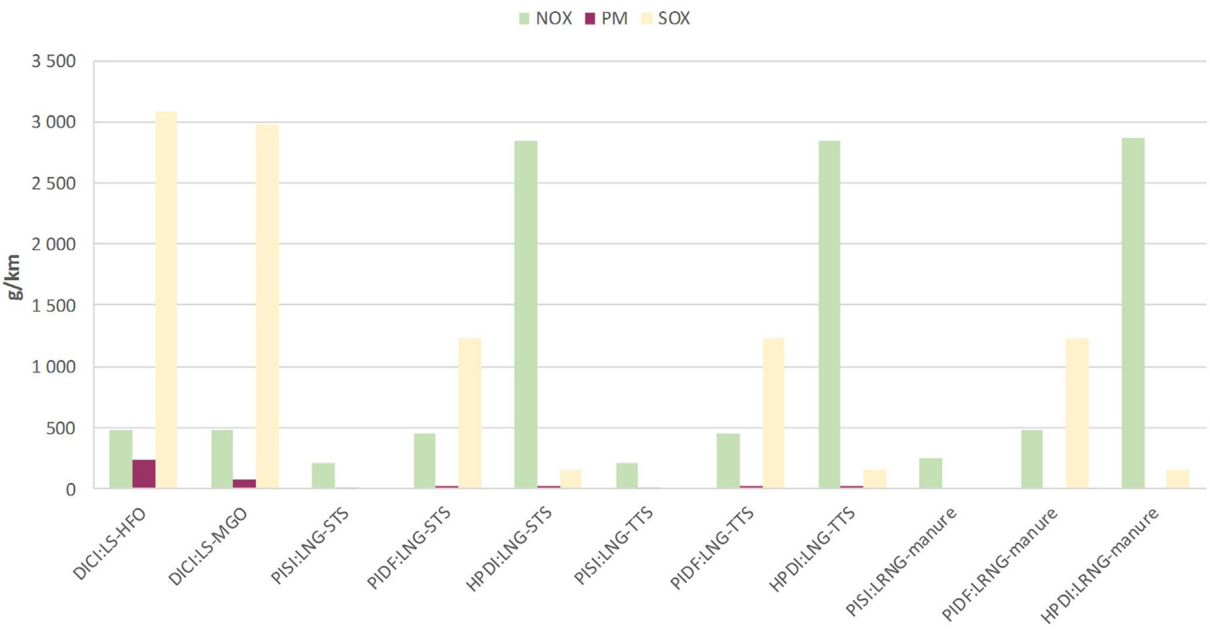

Fig. 14. WTW air pollutants emission of selected pathways for maritime transport application (passenger vessel).

compared to the reference vessel, 100% SOx (as SO_2) and 55% NOx emissions reductions are possible in all PISI engine pathways, but limited to 60% (SOx) and 95% (SOx) in PIDF and HPDI engine pathways, respectively, in proportion with their respective LS-HFO substitution rate. However, the HPDI showed higher NOx emissions due to its high compression ratio, and hence, higher operating temperature and lack of aftertreatment system as in HDV. Installing aftertreatment systems on large vessels is a very expensive option. There are very few large LNG carriers and LNG vessels equipped with HPDI engines globally (Stenersen and Thonstad, 2017).

Since, we have assumed a complete on-board combustion of CO_2 in all pathways, to make a consistent comparison between pathways, CO emissions are not shown in Fig. 14. It is also worth mentioning that, as opposed to HDV, in passenger vessel, a higher diesel substitution (above the assumed 60%), and hence, a higher SOx reduction, could be possible in PIDF engines.

4. Conclusions

The transition to a green transport system, or green energy system at large, requires a clear strategy and executable policies. To assist the transition, in addition to addressing non-techno-economic challenges, i.e. such as planning problems, bureaucracy in authorization/certification procedures, regulatory uncertainty, and administrative barriers, identifying energy efficient, environmental impact reducing, and cost effective decarbonisation pathways is important.

In this study, in the Danish context, we have evaluated the WTW energy consumption, GHG emissions, and regulated (air pollutant) emissions of selected pathways for a functional unit of 1 (one) km driving distance in road-transport and maritime transport applications. We compared the alternative gas pathways with conventional reference vehicles. In road-transport applications, Euro 6 gasoline vehicle is used as a reference vehicle for passenger car and LDV classes while Euro VI diesel is used for HDV class. For the maritime transport applications, MARPLO Annex VI compliant LS-HFO passenger vessel is used as a reference passenger vessel.

Use of CNG/LNG as a substitute to conventional fuels in all transport segments results in a 15–27% WTW GHG emissions reduction opportunity, and for a deep decarbonisation, 81–211% WTW GHG emissions reduction if CRNG/LRNG are used instead. Nevertheless, the decarbonisation is plausible at the cost expense of a higher WTW energy consumption, which put pressure on feedstocks availability and competition in a resource constrained world.

The air pollutant emissions evaluation showed substantial advantages in passenger car and LDV classes but limited advantages for the HDVs; only CO emissions reduction. This could be explained by the lean-burn strategy in the HDVs; the trade-off between fuel economy, NOx, and HC emissions. Thus, it is worth mentioning that consistent real driving cycle emissions, based on annual driving distances, for both conventional and NGVs would have been better to use for the evaluation of the absolute environmental advantages of NGVs in all classes. This is because engines with a substantial amount of idling and low load, as in refuse trucks, have lower duty cycle temperatures that are not enough to sustain oxidation in selective catalytic reduction (SCR) to control NOx and methane slip. On-board combustion constitutes a large part of the air pollutant emissions in all pathways, while only a small fraction comes from the upstream processes (WTT), like stationary combustion and road-transport used for energy transportation and distribution.

Methane leakage and methane slip are important factors that could potentially offset the inherent GHG emissions advantages of NG in transport. It was shown that a 1% methane leakage in the supply chain would substantially increase the net GHG emissions and reduce the impact-reducing effect of all gas pathways. Similarly, on average, a 1% methane slip from a PISI, PIDF, and HPDI LNG vessels would results in 8.5%, 4.7%, and 8% increase in net GHG emissions, respectively. Also, despite the lower methane slip level of

PISI gas engine compared to PIDF and HPDI gas engines, its lower fuel economy was large enough to offset its net GHG emissions advantage in all pathways where gas showed advantage over conventional fuels. Thus, in addition to reducing methane leakage associated with the fuel supply chain and methane slip in gas engines, improving the fuel economy of NGVs is an additional opportunity to increase net GHG emissions reduction. In fact, owing to the methane slip reductions, due to technological advancements in the past decade, and advancing gas engine technologies, there are chances for further reductions in methane slip and emissions at large in the years to come.

Even though the results are specific to Denmark, similar conclusions can be drawn for other countries with similar grid electricity mix and gas transportation distance, especially with regards to CRNG/LRNG use as its fuel infrastructures are less dependent on the gas transmission and distribution length. Most importantly, the insights as to the energy and environmental performances of PISI, PIDF, and HPDI gas engines are relevant for any country.

Finally, as noted in Section 3, the results are very sensitive to the various assumptions made throughout the report, such as, methane leakage and methane slip, type approved emissions and energy consumptions, the assumed gas yield of anaerobic digesters, and others. Therefore, the results should be interpreted with that in mind. Also, the WTW emissions profile of second-generation biomethane in Denmark was not addressed in this study, but should be included in future works to investigate its role for deep decarbonisation.

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Appendix A. Compressor work

The actual power required has been calculated from the ideal adiabatic compression work, as given by:

$$W_{min}\left[\frac{J}{kg}\right] = \frac{N*k*R*T_1*Z}{M*(k-1)}[[\frac{P_2}{P_1}]^{\frac{k-1}{N*k}}-1]$$

$$W_{actual}[W] = \frac{m*W_{min}}{\eta_{is}*\eta_m}$$

where m: mass flow (kg/s), R: universal gas constant (8.3145 J/(mole-K)), k specific heat ratio (1.32), T_1: inlet gas temperature (5 °C or 278 K), Z: compressibility factor (0.99), P_1: inlet pressure (4 bar), P_2: outlet pressure (230 bar), N: number of compressor stages (4), η_{is}: isentropic efficiency (80%), η_m: mechanical efficiency (99%), M: molar mass of NG (19 g/mole).

Appendix B. Type approved and real-world emissions

The passenger vessel fuel economy estimated assuming a vessel with a capacity of transporting 600 passengers and cruising in Emission Control Areas at 14 knot/h (16 miles/h).

$$Fueleconomy\left[\frac{km}{L}\right] = \left[\frac{10,600}{CAP^{2.2}} + \frac{10}{Vesselspeed^2}\right]*0.43$$

where CAP is the vessel capacity. In the formula, the vessel speed is expressed in miles/h (Cottrell, 2011) (see Tables B1–B4).

Table B1
Type-approved emissions limit (Euro 6 and Euro VI) of conventional vehicles (g/kWh) (DieselNet, 2016).

Emission	Gasoline car (M1 category)[a] g/km	Diesel car (M1 category)	Light duty vehicle gasoline (N1 class III)[b]	Light duty vehicle diesel (N1 class III)	Heavy duty vehicle (diesel CI) g/kWh	Heavy duty vehicle (diesel and gas PI)[c]
CO	1	0.5	2.27	0.74	1.5	4
NMHC	0.068	–	0.108	–	–	0.16[d]
CH_4	–	–	–	–	–	0.5
NOx	0.06	0.08	0.082	0.125	0.4	0.46
HC	0.1	–	0.16	–	0.13	–
HC + NO_X	–	0.17	–	0.215	–	–
PM	0.005	0.005	–	0.005	0.01	0.01
PN (1/kWh)	6×10^{11}	$6 * 10^{11}$	$6 * 10^{11}$	$6 * 10^{11}$	$8 * 10^{11}$	$6 * 10^{11}$

[a] M1 category refers to cars used for carriage of passengers, comprising not more than eight seats.
[b] N1 category class III vehicles refers to those LDVs used for the carriage of goods and having a maximum mass not exceeding 3.5 tonnes.
[c] Positive ignition (PI) refers to engines whose combustion is initiated by external energy source like spark plug or pilot diesel injection as the case in dual fuel engines. And, CI refers to compression ignition engines whose combustion is initiated by the compressed gas itself.
[d] This become the THC for diesel engines.

Table B2
Assumed emissions factor (real-world emissions) for passenger car, LD, and HD gas vehicles (g/kWh) (Olofsson et al., 2014; Rašić et al., 2017; Willner and Danielsson, 2014).

Emission	Passenger car and LD vehicle	HD vehicle		
	PISI g/km	PISI g/kWh	PIDF	HPDI
CO	0.228	1.87	0.03	0.0049
NMHC	0.0031	0.06	0.67	0.0019
CH_4	0.0155	0.27	6.53	0.84
NOx	0.0155	0.48	5.79	0.54
HC	0.16	–	7.2	–
HC + NO_X	–		–	–
PM	0.0001	0.006	0.006	0.0001

Table B3
Assumed emissions factor for convectional vessels (MARPOL Annex VI) and LNG vessels (real-world emissions) in ECAs (g/kWh) (Corbett et al., 2015; Nielsen and Stenersen, 2010).

Emission	Conventional vessels (g/kWh) Engine type	LNG vessels (g/kWh)		
	DICI Fuel	PISI	PIDF	HPDI
	HFO/MGO	LNG	LNG	LNG
CH_4	–	4.1	6.9	0.693
NO_X	2	0.9	1.9	12
SOx	0.1%	–		
PM2.5/10	5.1/1.7 g/kg	0.04	0.1	0.1
N_2O		0.015	0.015	0.015
NMHC		0.03	0.4	0.5

Table B4
WTT energy and emissions for low sulfur marine fuels (Baldi et al., 2013).

	LS-HFO	LS-MGO
WTT attributes		
Primary energy[a] (MJ/MJ_{fuel})	0.09	0.16
CO_2 (g/MJ_{fuel})	6.68	7.02
CH_4 (g/MJ_{fuel})	0.073	0.078
N_2O (g/MJ_{fuel})	0.0002	0.0002
Chemical properties of low sulfur marine fuels		
Density, kg/m^3 at 15 °C	968	795
LHV, MJ/kg	40.96	42.65
S%	0.1	0.1

[a] The primary energy does not include the final energy content of the fuel, i.e. 1 MJ.

Appendix C. Primary energy and emissions associated with the production of synthetic fertilisers

The nutrients content of the manure and waste digestate are estimated for a unit MW of raw biogas production from each feedstock (see Tables C1 and C2).

Table C1
Primary energy and emissions associated with the production of synthetic fertilisers (Joint Research Centre (JRC), 2014).

Input commodity	N (as N) Primary energy (MJ/kg of nutrient)	P (as P_2O_5)	K (as K_2O)
NG	65	3.59	8.55
Crude oil	0.89	–	–
Diesel	–	1.34	0.65
HFO	–	5	–
Coal	0.21	2.1	–
Electricity-EU Mix	–	4.85	0.67
Electricity-Hydro	0.06	–	–
Electricity-Nuclear	0.19	–	–
Emissions (g/kg of nutrient)			
CO_2	3794	700	453
N_2O	7.315	0.042	0.009
CH_4	7.93	0.02	0.02

Table C2
Nutrients content of manure and municipal organic waste digestate.

Nutrient	Manure (cattle & pig) Nutrient content (g_N/MJ_{rawgas})	Municipal organic waste
Nitrogen (N)	12.16	0.56
Phosphorous (P)	9.11	0.1
Potassium (K)	2.73	0.22

References

Alamia, A., Magnusson, I., Johnsson, F., Thunman, H., 2016. Well-to-wheel analysis of bio-methane via gasification, in heavy duty engines within the transport sector of the European Union. Appl. Energy 170, 445–454.
Arteconi, A., Brandoni, C., Evangelista, D., Polonara, F., 2010. Life-cycle greenhouse gas analysis of LNG as a heavy vehicle fuel in Europe. Appl. Energy 87, 2005–2013.
Baldi, F., Brynolf, S., Andersson, K., 2013. The influence of propulsion system design on the carbon footprint of different marine fuels.
Bang, H.J., Stockar, S., Muratori, M., Rizzoni, G., 2014. Modeling and Analysis of a CNG Residential Refueling System. V003T037A005.
Bauer, F., Hulteberg, C., Persson, T., Tamm, D., 2013. Biogas Upgrading – Review of Commercial Technologies. Swedish Gas Centre (SGC).
Beer, T., Grant, T., Williams, D., Watson, H., 2002. Fuel-cycle greenhouse gas emissions from alternative fuels in Australian heavy vehicles. Atmos. Environ. 36, 753–763.
BISYPLAN web-based handbook, 2012.
Bundgaard, S.S., Kofoed-Wiuff, A., Herrmann, I.T., Karlsson, K.B., 2014. Experiences with Biogas in Denmark. Department of Management Engineering, Technical University of Denmark.
Bunker Holding, P.o.F.a.K.C., 2016. LNG Liquefaction Plant in Northern Denmark. Bunker Holding, Port of Frederikshavn and Kosan Crisplant.
Choi, W., Song, H.H., 2014. Well-to-wheel analysis on greenhouse gas emission and energy use with natural gas in Korea. Int. J. Life Cycle Assess. 19, 850–860.
Chryssakis, C., Brinks, H., King, T., 2015. The Fuel Trilemma: Next Generation of Marine Fuels. DNV GL.
Corbett, J.J., Thomson, H., Winebrake, J.J., 2015. Methane Emissions from Natural Gas Bunkering Operations in the Marine Sector: A Total Fuel Cycle Approach. U.S. Department of Transportation.
Cottrell, W.D., 2011. Comparison of ferry boat and highway bridge energy use. Energies 4, 239.
Curran, S.J., Wagner, R.M., Graves, R.L., Keller, M., Green Jr., J.B., 2014. Well-to-wheel analysis of direct and indirect use of natural gas in passenger vehicles. Energy 75, 194–203.
Danish Gas Technology Centre, 2016. Natural Gas in Denmark. Naturgasnettet i Danmark (in Danish).
DieselNet, 2016. Heavy-Duty Truck and Bus Engines.
dieselNet, 2017. Volvo introduces LNG powered Euro VI trucks.
DONG energy, 2013a. Annnual environmental report of Nybro gas treatment plant. Nybro Gasbehandlingsanlæg: Miljöregnskab 2013 (in Danish).
DONG energy, 2013b. Annual environmental report of Stenlille gas storage plant. Gönt Regnskab for 2013 (in Danish).
Durbin, T.D., Johnson, K., Miller, J.W., Maldonado, H., Chernich, D., 2008. Emissions from heavy-duty vehicles under actual on-road driving conditions. Atmos. Environ. 42, 4812–4821.
Eise Fokkema, J., Buijs, P., Vis, I.F.A., 2017. An investment appraisal method to compare LNG-fueled and conventional vessels. Transp. Res. Part D: Transp. Environ. 56, 229–240.
ENERGINET.DK, 2012. Technology Data for Energy Plants. ENERGINET.DK.
EnergiNet.DK, 2017. Future Natural Gas Qualities – Fact sheet.
Engerer, H., Horn, M., 2010. Natural gas vehicles: an option for Europe. Energy Policy 38, 1017–1029.
European Environmental Agency, 2017. Transport Greenhouse Gas Emissions. European Environmental Agency.
Fontaras, G., Martini, G., Manfredi, U., Marotta, A., Krasenbrink, A., Maffioletti, F., Terenghi, R., Colombo, M., 2012. Assessment of on-road emissions of four Euro V diesel and CNG waste collection trucks for supporting air-quality improvement initiatives in the city of Milan. Sci. Total Environ. 426, 65–72.
German Energy Agency (DENA), 2014. LNG in Germany: Liquefied Natural Gas and Renewable Methane in Heavy-Duty Road Transport. German Energy Agency (DENA).
Hagos, D.A., Ahlgren, E., 2017. A state-of-the art review on the development of CNG/LNG infrastructure and natural gas vehicles (NGVs). In: Technology, C.U.o. (Ed.).
Hegab, A., La Rocca, A., Shayler, P., 2017. Towards keeping diesel fuel supply and demand in balance: dual-fuelling of diesel engines with natural gas. Renew. Sustain. Energy Rev. 70, 666–697.
Huai, T., Shah, S.D., Wayne Miller, J., Younglove, T., Chernich, D.J., Ayala, A., 2006. Analysis of heavy-duty diesel truck activity and emissions data. Atmos. Environ.

40, 2333–2344.
Huo, H., Yao, Z., Zhang, Y., Shen, X., Zhang, Q., Ding, Y., He, K., 2012. On-board measurements of emissions from light-duty gasoline vehicles in three mega-cities of China. Atmos. Environ. 49, 371–377.
Høibye, G., 2014. Norwegian NOx Fund as a driving force for LNG use. Næringslivets NOx-fond.
International Association for Natural Gas Vehicles (IANGV), 2016. Latest International NGV Statistics.
International Maritime Organization (IMO), 2016. Sulphur oxides (SOx) – Regulation 14.
IPCC2006, 2006. Chapter 4: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. Prepared by the National Greenhouse Gas Inventories Programme, IPCC, Japan.
Jafarzadeh, S., Paltrinieri, N., Utne, I.B., Ellingsen, H., 2017. LNG-fuelled fishing vessels: a systems engineering approach. Transp. Res. Part D: Transp. Environ. 50, 202–222.
Joint Research Centre (JRC), 2014. Well-to-Wheels analysis of future automotive fuels and powertrains in the European context, version 4.a, January 2014.
Jørgensen, P.J., 2009. Biogas – Green Energy, second ed. Faculty of Agricultural Sciences, Aarhus University.
Kadam, R., Panwar, N.L., 2017. Recent advancement in biogas enrichment and its applications. Renew. Sustain. Energy Rev. 73, 892–903.
Karavalakis, G., Durbin, T.D., Villela, M., Miller, J.W., 2012. Air pollutant emissions of light-duty vehicles operating on various natural gas compositions. J. Nat. Gas Sci. Eng. 4, 8–16.
King & Spalding LLP, 2015. LNG in Europe: An Overview of European Import Terminals in 2015. King & Spalding LLP.
Lou, D.M., Qian, S.L., Hu, Z.Y., Tan, P.Q., 2013. On-road gaseous emission characteristics of China IV CNG bus in Shanghai. Adv. Mater. Res. 690–693, 1864–1871.
McKenzie, E.C., Durango-Cohen, P.L., 2012. Environmental life-cycle assessment of transit buses with alternative fuel technology. Transp. Res. Part D: Transp. Environ. 17, 39–47.
Mintz, M., Han, J., Wang, M., Saricks, C., 2010. Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model. Center for Transportation Research, Energy Systems Division, Argonne National Laboratory.
Natural & bio Gas Vehicle Association (NGVA) Europe, 2016. Report of activities 2015/2016.
Nielsen, J.B., Stenersen, D., 2010. Emission factors for CH4, NOx, particulates and black carbon for domestic shipping in Norway, revision 1. MARINTEK.
Niesner, J., Jecha, D., Stehlík, P., 2013. Biogas upgrading technologies: state of art review in European Region. Chem. Eng. Trans. 35, 517–522.
Nordic Energy Technology Perspectives 2016, 2016. Cities, Flexibility and Pathways to Carbon-neutrality. International Energy Agency, France.
Näslund, M., 2012. LNG – Status in Denmark. Danish Gas Technology Centre.
Olofsson, M., Erlandsson, L., Willner, K., 2014. Enhanced Emission Performance and Fuel Efficiency for HD Methane Fuelled Engines. International Energy Agency (IEA).
Osorio-Tejada, J.L., Llera-Sastresa, E., Scarpellini, S., 2017. Liquefied natural gas: could it be a reliable option for road freight transport in the EU? Renew. Sustain. Energy Rev. 71, 785–795.
Persson, M., Jönsson, O., Wellinger, A., 2006. Biogas upgrading to vehicle fuel standards and grid injection, IEA-Bioenergy task 37 – Energy from Biogas and Landfill Gas. IEA.
Plejdrup, M.S., Nielsen, O.-K., Nielsen, M., 2015. Emission Inventory for Fugitive Emissions from Fuel in Denmark. Aarhus University, Department of Environmental Science.
Rašić, D., Rodman Oprešnik, S., Seljak, T., Vihar, R., Baškovič, U.Ž., Wechtersbach, T., Katrašnik, T., 2017. RDE-based assessment of a factory bi-fuel CNG/gasoline light-duty vehicle. Atmos. Environ. 167, 523–541.
Rosenfeld, J., Jackson, M.D., 2008. Life-cycle Cost Model and Pollutant Emissions Estimator. Westport Innovations Inc. TIAX LLC.
Saadat-Targhi, M., Khadem, J., Farzaneh-Gord, M., 2016. Thermodynamic analysis of a CNG refueling station considering the reciprocating compressor. J. Nat. Gas Sci. Eng. 29, 453–461.
Seadi, T.A., 2000. Danish Centralised Biogas Plants – Plant Descriptions. Bioenergy Department, University of Southern Denmark.
Shen, W., Han, W., Chock, D., Chai, Q., Zhang, A., 2012. Well-to-wheels life-cycle analysis of alternative fuels and vehicle technologies in China. Energy Policy 49, 296–307.
Stenersen, D., Thonstad, O., 2017. GHG and NOx Emissions from Gas Fuelled Engines. SINTEF Ocean AS.
Tuong-Van, N., Erasmus Damgaard, R., Brian, E., Allan, H.B., 2016. Techno-economic optimisation of three gas liquefaction processes for small-scale applications. In: Proceedings of ECOS 2016: 29th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.
Ward, A.J., Hobbs, P.J., Holliman, P.J., Jones, D.L., 2008. Optimisation of the anaerobic digestion of agricultural resources. Bioresour. Technol. 99, 7928–7940.
Willner, K., Danielsson, D., 2014. Testing of Unregulated Emissions from Heavy Duty Natural Gas Vehicles-Part II. Swedish Gas Technology Centre (SGC).
Wurster, R., Weindorf, W., Zittel, W., Schmidt, P., Heidt, C., Lambrecht, U., Lischke, A., Müller, S., 2014. LNG as an alternative fuel for the operation of ships and heavy-duty vehicles: short study in the context of the National Mobility and Fuel Strategy. DLR, IFEU, LBST, DBFZ., Munich.
Yao, Z., Cao, X., Shen, X., Zhang, Y., Wang, X., He, K., 2014. On-road emission characteristics of CNG-fueled bi-fuel taxis. Atmos. Environ. 94, 198–204.
Yazdanie, M., Noembrini, F., Heinen, S., Espinel, A., Boulouchos, K., 2016. Well-to-wheel costs, primary energy demand, and greenhouse gas emissions for the production and operation of conventional and alternative vehicles. Transp. Res. Part D: Transp. Environ. 48, 63–84.
Zhang, C.H., Xie, Y.L., Wang, F.S., Ma, Z.Y., Qi, D.H., Qiu, Z.W., 2010. Emission comparison of light-duty in-use flexible-fuel vehicles fuelled with gasoline and compressed natural gas based on the ECE 15 driving cycle. Proc. Inst. Mech. Eng., Part D: J. Automob. Eng. 225, 90–98.
Zhang, S., Wu, Y., Liu, H., Huang, R., Yang, L., Li, Z., Fu, L., Hao, J., 2014. Real-world fuel consumption and CO_2 emissions of urban public buses in Beijing. Appl. Energy 113, 1645–1655.
Zunder, T.H., Ibanez, J.N., 2004. Urban freight logistics in the European Union European Transport 28.